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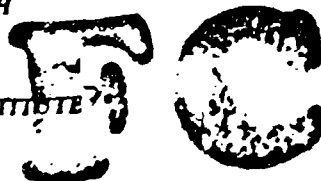
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MATERIALS-PROPERTY-DESIGN CRITERIA FOR METALS

PART 5. THE CONVENTIONAL SHORT-TIME, ELEVATED-TEMPERATURE
PROPERTIES OF SELECTED STAINLESS STEELS AND SUPER ALLOYS

RONALD J. FAVOR
WILLIAM P. ACHBACH
WALTER S. HYLER

BATTELLE MEMORIAL INSTITUTE



OCTOBER 1957

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MATERIALS LABORATORY
CONTRACT NO. AF 33(616)-2303
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WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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FOREWORD

This report was prepared by Battelle Memorial Institute, Columbus, Ohio, under Contract No. AF 33(616)-2303. The investigation was initiated under Project No. 7360, "Materials Analysis and Evaluation Techniques", Task No. 73605, "Design Data for Metals". It was administered under the direction of the Materials Laboratory, Directorate of Laboratories, Wright Air Development Center with Mr. D. A. Shinn acting as project engineer.

This research has been carried out under the supervision of H. J. Grover, Chief of the Applied Mechanics Division, with considerable valuable consultation from S. A. Gordon. Other Battelle staff members who participated to a considerable extent in the program include A. H. Hunter, N. J. Weller, W. L. Belton, and L. E. Hanna.

This report covers work conducted from January 1, 1956, to December 15, 1956.

ABSTRACT

Presented in this report is a compilation of data on the conventional short-time, elevated-temperature properties of selected corrosion-resistant and high-temperature alloys applicable to airframe and missile fabrication. The resultant recommended design data obtained in this study have been presented in such form as to be directly applicable to the ANC-5 Bulletin (issued by the Air Force-Navy-Civil Panel) on "Strength of Metal Aircraft Elements".

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:



R. R. KENNEDY
Chief, Metals Branch
Materials Laboratory

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MATERIALS-PROPERTY-DESIGN CRITERIA FOR METALS

PART 5. THE CONVENTIONAL SHORT-TIME, ELEVATED-TEMPERATURE PROPERTIES OF SELECTED STAINLESS STEELS AND SUPER ALLOYS

INTRODUCTION

The design strength properties of materials for airframe and missile fabrication presented in the ANC-5 (Air Force-Navy-Civil) Bulletin, "Strength of Metal Aircraft Elements". As the needs of designers in these fields crystallize, revisions of the document are required to introduce new information into the Bulletin or revise current information as more reliable data become available. The purpose of this investigation has been, broadly, to study various aspects pertinent to design criteria as suggested by the Materials Laboratory of Wright Air Development Center and to present the results of such studies in a format consistent with the present ANC-5 Bulletin for possible consideration by the ANC-5 Panel.

It should be emphasized that the recommended design curves included herein are not necessarily identical to any which will ultimately appear in ANC-5. Use of any data appearing herein is therefore subject to approval by the cognizant procuring or certifying agency.

This report represents the fifth report in this series. The four previous reports are:

- (1) WADC TR 55-150, Part 1, "Materials-Property-Design Criteria for Metals; Part 1" (January, 1956).
- (2) WADC TR 55-150, Part 2, "Materials-Property-Design Criteria for Metals; Part 2, A Study of Methods of Presenting Creep Data for Airframe Design", by W. S. Hyler and H. J. Grover (July, 1955).
- (3) WADC TR 55-150, Part 3, "Materials-Property-Design Criteria for Metals; Part 3, Fatigue Evaluation of Magnesium Alloys", by W. S. Hyler and F. H. Lyon (June, 1956).
- (4) WADC TR 55-150, Part 4, "Materials-Property-Design Criteria for Metals; Part 4, Elastic Moduli: Their Determination and Limits of Application", by S. A. Gordon, R. Simon, and W. P. Achbach (August, 1956).

Manuscript received by ADAS on March 2, 1957, for publication as a WADC Technical Report.

The purpose of this present study is to compile and present data on the conventional short-time, elevated-temperature properties of a number of stainless steels and heat-resistant alloys which are of current interest in airframe and missile fabrication. It is the aim of this report to provide a basis upon which it would be possible to supplement and revise the current issue of the ANC-5 Manual. It is not intended that any discrepancy exist between data contained in this report and data found in the current ANC-5 Bulletin. If such discrepancies are noted, the ANC-5 values of strength are to be used.

As a result of mutual agreement between representatives of the Materials Laboratory of Wright Air Development Center and of Battelle Memorial Institute, the following commercial alloys are included in this report of stainless steels and heat-resistant alloys: (1) AISI 301 (half hard and full hard), (2) 422M, (3) 17-7PH (TH 1050 and TH 950), (4) AM-350, (5) 17-4PH, (6) 19-9DL, (7) 19-9DX, (8) A-286, (9) Inconel "X", and (10) Stainless "W". It was intended that data be presented on AISI 420 stainless steel; however, no pertinent data were found available for this material. A brief discussion of each alloy is found in the separate sections of this report.

For convenience, design curves from each of the specific material sections are summarized at the end of the report. Appendix I contains some material-comparison curves.

The authors wish to acknowledge the materials producers, airframe manufacturers, universities, research laboratories, and Government agencies listed below without whose assistance this investigation would not have been possible. A Bibliography is included in Appendix II.

Allegheny Ludlum Steel Corporation
Armco Steel Corporation
Babcock and Wilcox Tube Company
Carpenter Steel Company
Crucible Steel Company of America
Haynes Stellite Company
International Nickel Company
Republic Steel Corporation
Timken Roller Bearing Company
United States Steel Corporation
Universal Cyclops Steel Corporation
Vanadium-Alloys Steel Company
Boeing Airplane Company
Chance Vought Aircraft, Inc.
Douglas Aircraft, Inc.
General Electric Company
Glenn L. Martin Company
North American Aviation, Inc.
Armour Research Foundation

Southern Research Institute
Titanium Metallurgical Laboratory
(Battelle)
University of California
Cornell Aeronautical Laboratory
Johns Hopkins Applied Physics
Laboratory
University of Michigan Research
Foundation
Syracuse University
U. S. Department of Commerce
(Aircraft Structures Branch)
U. S. Department of Commerce
(Materials Branch)
National Advisory Committee on
Aeronautics
National Bureau of Standards
Wright Air Development Center
(Materials Laboratory)

METHOD OF APPROACH

General Comments

As indicated in the "Introduction", a large number of sources were contacted in assembling the data from which the study was based. These included material producers, universities, research laboratories, Government agencies, and the open literature.

The properties of interest included tensile, compressive, shear, and bearing strengths. Assessment of these properties as a function of temperature, exposure time, strain rate, etc., was made, consistent with available data. For a number of alloys, considerable information was available on many of these properties; in other cases only a few properties had been evaluated. Thus, there developed in some cases large gaps which can be taken care of only by careful experimental programs.

The next several subsections relate in detail the approaches used in analyzing the large body of data. It should be pointed out that the goal was to provide conservative "design" curves of a form currently used in ANC-5. For alloys involving considerable data from a number of sources, procedures were adopted to account for differences in the data to prepare such design curves. Discussion of trends observed in the design curves was beyond the scope of the program.

Each alloy is considered in a major section of the report. This includes a brief description of the alloys and usual heat treatments, various graphs showing the relationships between mechanical properties and temperature, stress-strain curves, etc. A final major section contains the recommended design curves for the entire group of alloys.

In a number of cases mechanical properties were available from specimens sectioned transverse and longitudinal to the major working direction. In these cases both sets of properties were treated separately. In the following sections, curves treating transverse properties are so indicated in the graphs.

The standard structural symbols used throughout this report are:

- F_{tu} Ultimate tensile stress
- F_{ty} Tensile yield stress
- F_{cy} Compressive yield stress
- F_{su} Ultimate shear stress

F_{bru}	Ultimate bearing stress
F_{bry}	Bearing yield stress
G	Modulus of rigidity
μ	Poisson's ratio
ksi	Kips (1000 pounds) per square inch
psi	Pounds per square inch
E	Modulus of elasticity in tension; average ratio of stress to strain below proportional limit
E_c	Modulus of elasticity in compression; average ratio of stress to strain below proportional limit.

Treatment of Strength Properties F_{tu} , F_{ty} ,
 F_{cy} , F_{su} , F_{bru} , and F_{bry}

Data From One Source

When data showing the effect of temperature (for any unique condition) on any of the above strength properties were available from only one source, no analysis was necessary. The data were presented in two ways. In the first presentation the actual stress value was plotted against temperature; in the second, the stress value as a percentage of the room-temperature property was plotted against temperature. This second curve is in such format as to be readily inserted in the ANC-5 Bulletin on "Strength of Metal Aircraft Elements".

Data From More Than One Source

(F_{tu}). The actual stress values for this strength property are plotted on one graph against temperature for all sources of data. A second graph was prepared showing all the data from all sources plotted as a percentage of room-temperature ultimate tensile strength against temperature. This second graph also shows the design curve that had been approximated from the data. A final third graph was prepared showing only the recommended design curve in such format as to be readily inserted in the ANC-5 Bulletin.

(F_{ty} , F_{cy} , F_{su} , F_{brg} , and F_{bry}). The actual stress values for these properties were plotted against temperature as for F_{tu} . A working curve then was drawn which showed the ratio of the above properties to the ultimate tensile strength (F_{tu}) for the corresponding temperature (these working curves do not appear in this report). In some cases, a straight-line relationship or at least a realistic trend to the data was apparent. Values from the working curves then were utilized in establishing the relationship between the mechanical property and temperature. The determined property expressed as a percentage of the room-temperature property was plotted on a graph using data from all sources. Again, a separate graph was prepared indicating the recommended design curve in ANC-5 format. In those cases in which it was not possible to establish a realistic trend in the plots of the ratio of mechanical property to ultimate strength versus temperature, a conservative estimate was utilized in developing design curves.

Treatment of Modulus of Elasticity (E and E_c) and Stress-Strain Data (Optimization Process)

General

The extensive data obtained for this study provided, in general, considerable variation in modulus of elasticity and in the shapes of stress-strain curves of various materials. The degree of scatter in modulus of elasticity is indicated for one material in Figure 1. To permit analyses of all the data for consistency, the following steps were taken:

- (1) Determine the "optimum" modulus of elasticity-temperature relationship
- (2) Adjust the stress-strain curves to fit the optimum modulus for each particular temperature.

Determination of the optimum modulus of elasticity-temperature relationship was achieved by the method of polynomial regression (readily adaptable to IBM computation). This system provides (a) a method of approximating the underlying relationship of variables by means of a polynomial equation of the form

$$Y = C_0 + C_1 X + C_2 X^2 + \dots + C_n X^n ,$$

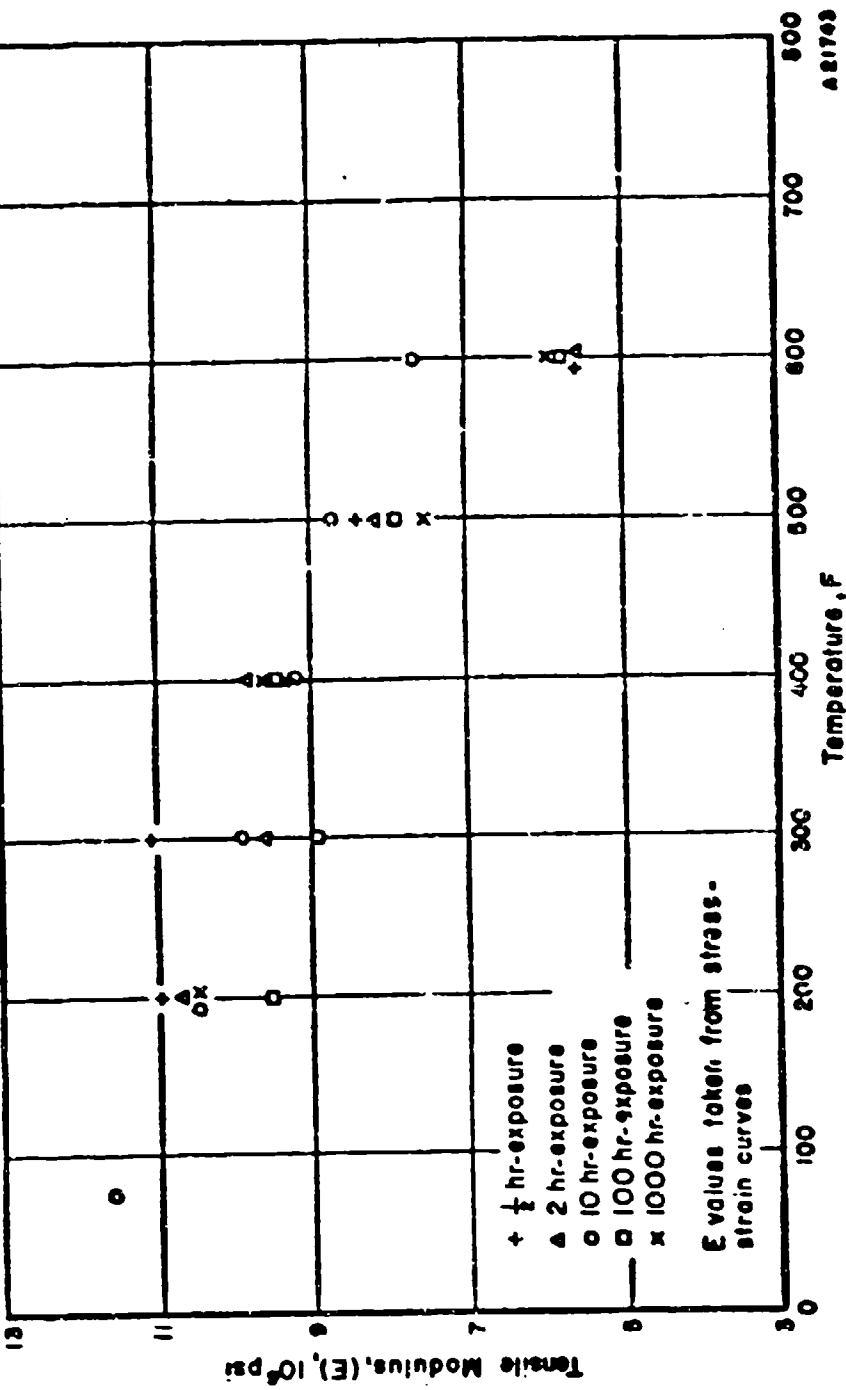


FIGURE 1. TENSILE MODULUS VERSUS TEMPERATURE FOR 2014-T6 CLAD ALUMINUM ALLOY

Ref. 58.

where

Y , the dependent variable, is the modulus of elasticity in psi,

X , the independent variable, is the temperature in degrees F, and

C_0, \dots, C_n are the constant coefficients to be estimated;

(b) a method of estimating these coefficients for a polynomial of a given degree from a set of paired observations on the modulus of elasticity and temperature; and (c) a method of determining the degree of the polynomial equation which the data indicate is warranted and significant.

It was determined that a polynomial of first or, at most, the second degree would approximate all the data for the various materials and conditions:

(a) $Y = a + bX$ and

(b) $Y = a + bX + cX^2$.

Figure 2 shows a curve approximated by this method and also shows the data from which the curve was derived.

The value thus determined for the modulus of elasticity at any given temperature was called the "optimized" value. Stress-strain curves for those materials and conditions for which an optimized modulus has been determined were adjusted so that the modulus agreed with the optimized value. The exception to this was that whenever the AEC-5 Bulletin reported a room-temperature modulus, this value was used in preference to any other.

Mathematical Details of Optimization of Modulus Data

The effect of temperature on the modulus of elasticity can be represented by the equation

$$\hat{Y} = a + bX$$

where

X is the temperature and

Y is the modulus of elasticity.

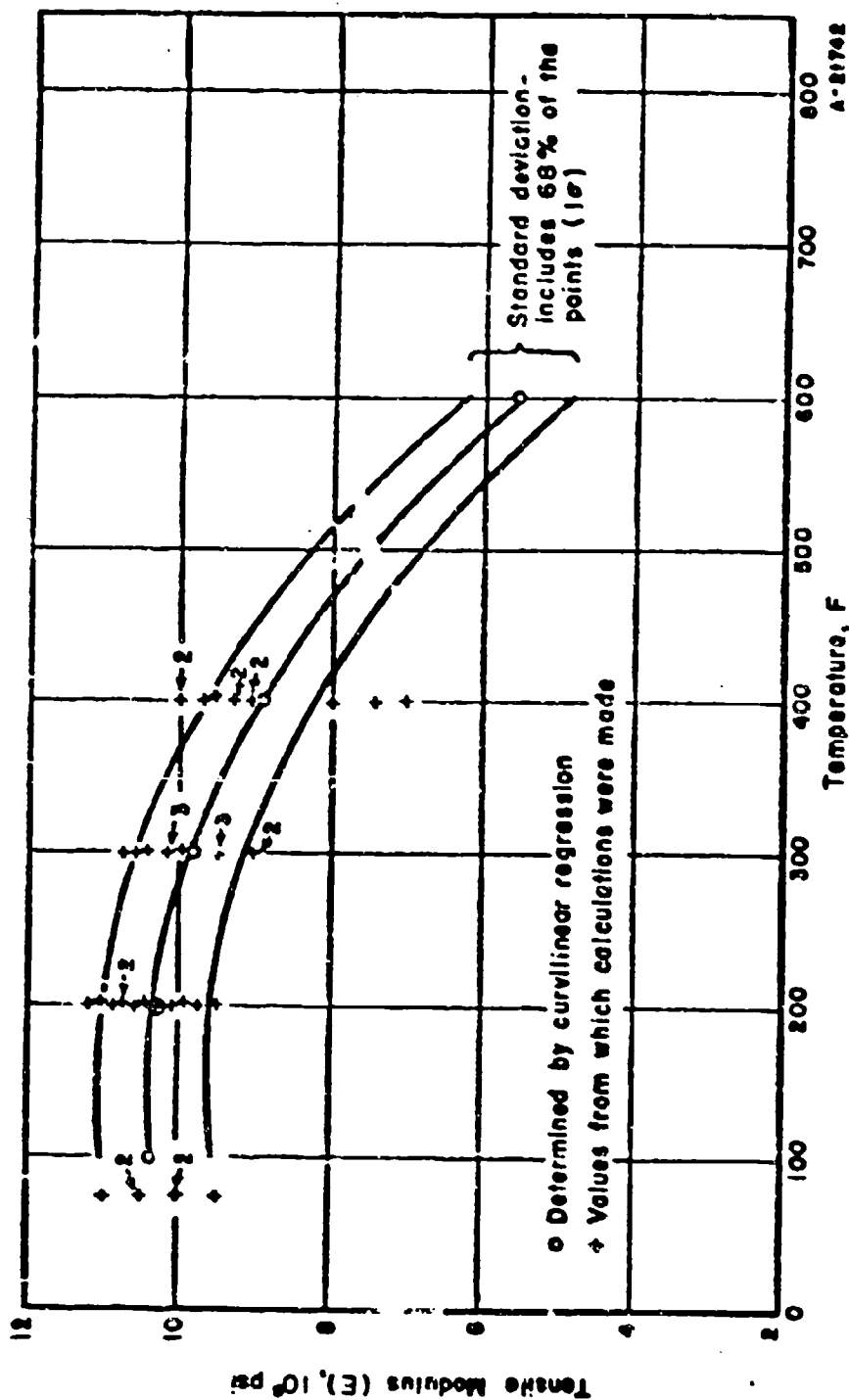


FIGURE 2. TENSILE MODULUS VERSUS TEMPERATURE FOR 2024-T81 ALUMINUM ALLOY

Ref. 98.

The symbol \hat{Y} means that Y is to be regressed on X; in other words, \hat{Y} is the estimated or predicted Y given the temperature X. The slope "b" of the regression equation is the regression coefficient and mathematically is

$$b = \frac{\sum xy}{\sum x^2} ,$$

where x and y are the deviations from the mean \bar{X} and \bar{Y} .

The intercept "a" is approximated by $a = \bar{Y} - b\bar{X}$ where $\bar{Y} = \frac{\sum Y}{n}$ and $\bar{X} = \frac{\sum X}{n}$.

It can be seen from Figure 3 that Y is composed of three segments: \bar{y} , \hat{y} , and $dy \cdot x$. The quantity $dy \cdot x$ is the deviation from regression and is defined mathematically as

$$Y - \hat{Y} = dy \cdot x .$$

Using the relation $Y = \bar{Y} + \hat{y} + dy \cdot x$ and $\sum Y = \sum \bar{Y} + \sum \hat{y} + \sum dy \cdot x$, squaring both sides results in

$$\sum Y^2 = \sum \bar{Y}^2 + \sum \hat{y}^2 + \sum dy \cdot x^2 ,$$

the three product terms being zero.

The least-squares curve can be fitted to the data such that $\sum dy \cdot x^2$ is a minimum and $\frac{\sum \hat{y}}{\sum dy \cdot x}$ equals zero. Standard methods of analysis were utilized in determining how well the derived curve fitted the data.



A vertical strip of film showing a repeating pattern of dark, irregular shapes on a light background, likely representing a microscopic view of a material surface. The pattern consists of dark, somewhat rounded, and irregular shapes that appear to be arranged in a regular, repeating fashion along the length of the strip. The background is a light, grainy texture. The overall appearance is that of a high-contrast, black-and-white image, possibly a micrograph or a film strip showing a material's surface structure.

AISI 301 STAINLESS STEEL
(QQ-S-682, FS 301)
(MIL-S-5059, Comp 301, half and full hard)

AISI 301 is an austenitic stainless steel which has the nominal composition shown in Table 1.

**TABLE 1. NOMINAL CHEMICAL
COMPOSITION OF
AISI 301 STAINLESS
STEEL (QQ-S-682,
FS 301)**

Element	Weight Per Cent
Carbon	0.12
Chromium	17.00
Nickel	7.00
Iron	Balance

The relative proportion of chromium and nickel enables AISI 301 to work harden rapidly when cold worked; the steel is well suited to high-strength applications. Minimum representative mechanical properties of the half-hard and full-hard tempers are given in Table 2.

**TABLE 2. MINIMUM REPRESENTATIVE MECHANICAL
PROPERTIES OF AISI 301 STAINLESS STEEL
(QQ-S-682, FS 301)**

Property	Half Hard (AMS-5510C 1/2 Hard)	Full Hard (AMS-5519E Hard)
Ultimate tensile (F _{tu})	150,000 psi	185,000 psi
Tensile yield (F _{ty})	110,000 psi	140,000 psi
Elongation (e) in 2 inches		
Thickness 0.015 inch and under	15 per cent	8 per cent
Thickness over 0.015 inch	18 per cent	9 per cent
Hardness	32 RC	41 RC

The temper conditions, half hard and full hard, are established by the tensile strength, which in this case is 150,000 psi minimum and 185,000 psi minimum, respectively.

The short-time, elevated-temperature data for the half-hard and full-hard tempers are shown in the following curves:

- (1) Tensile properties, Figures 4 through 11, and 36 through 42
- (2) Compressive properties, Figures 12 through 13
- (3) Bearing properties, Figures 14 through 19
- (4) Shear properties, Figures 20 through 21
- (5) Modulus of elasticity, Figures 22 through 30
- (6) Stress-strain curves, Figures 23 through 29, and 31 through 35

For 301 half hard, data are meager for compressive and shear properties; for 301 full hard only tensile properties are available.

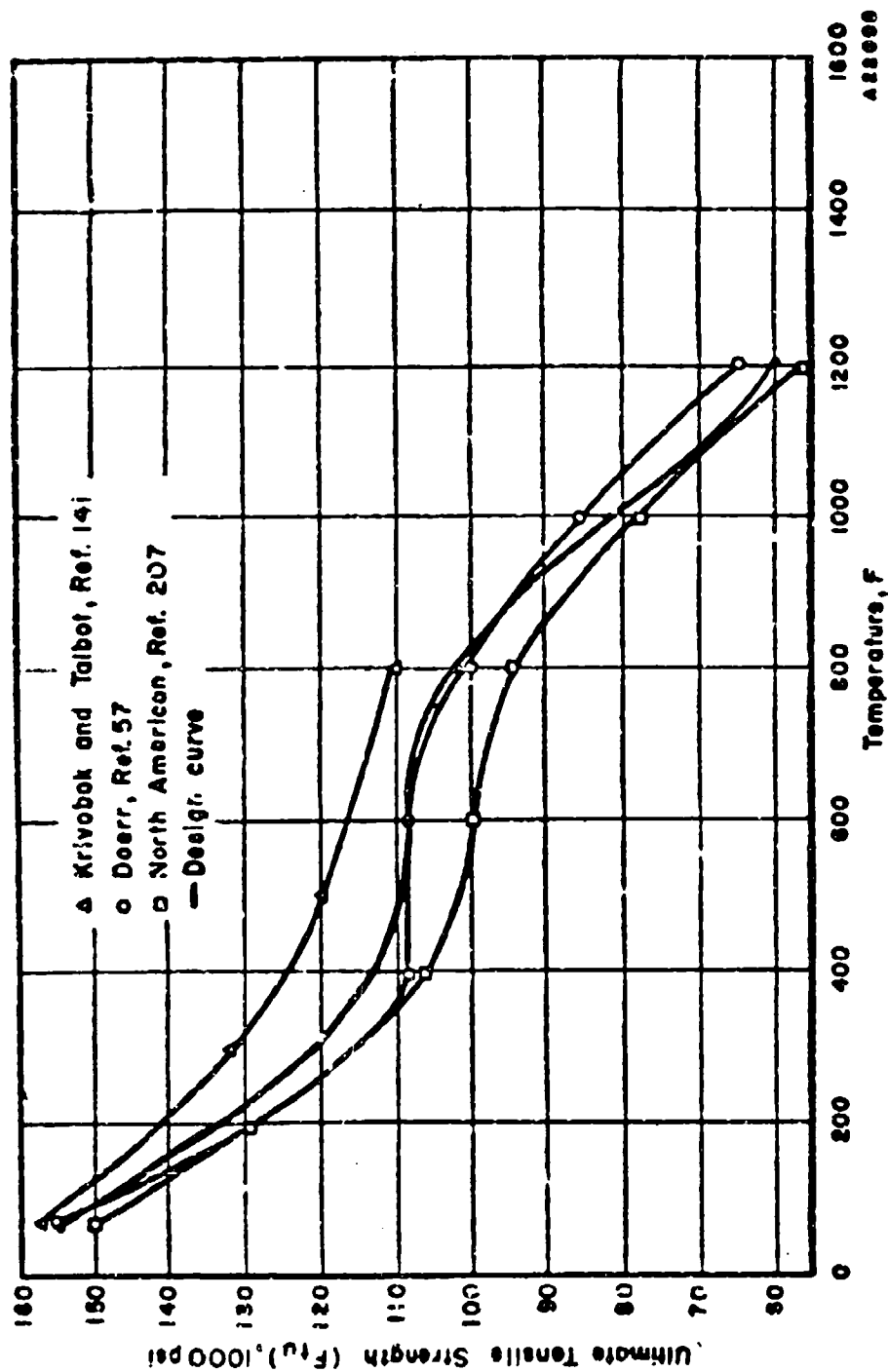


FIGURE 4. TENSILE STRENGTH (F_{tu}) OF AISI 301 (HALF HARD, STAINLESS STEEL AT ELEVATED TEMPERATURE

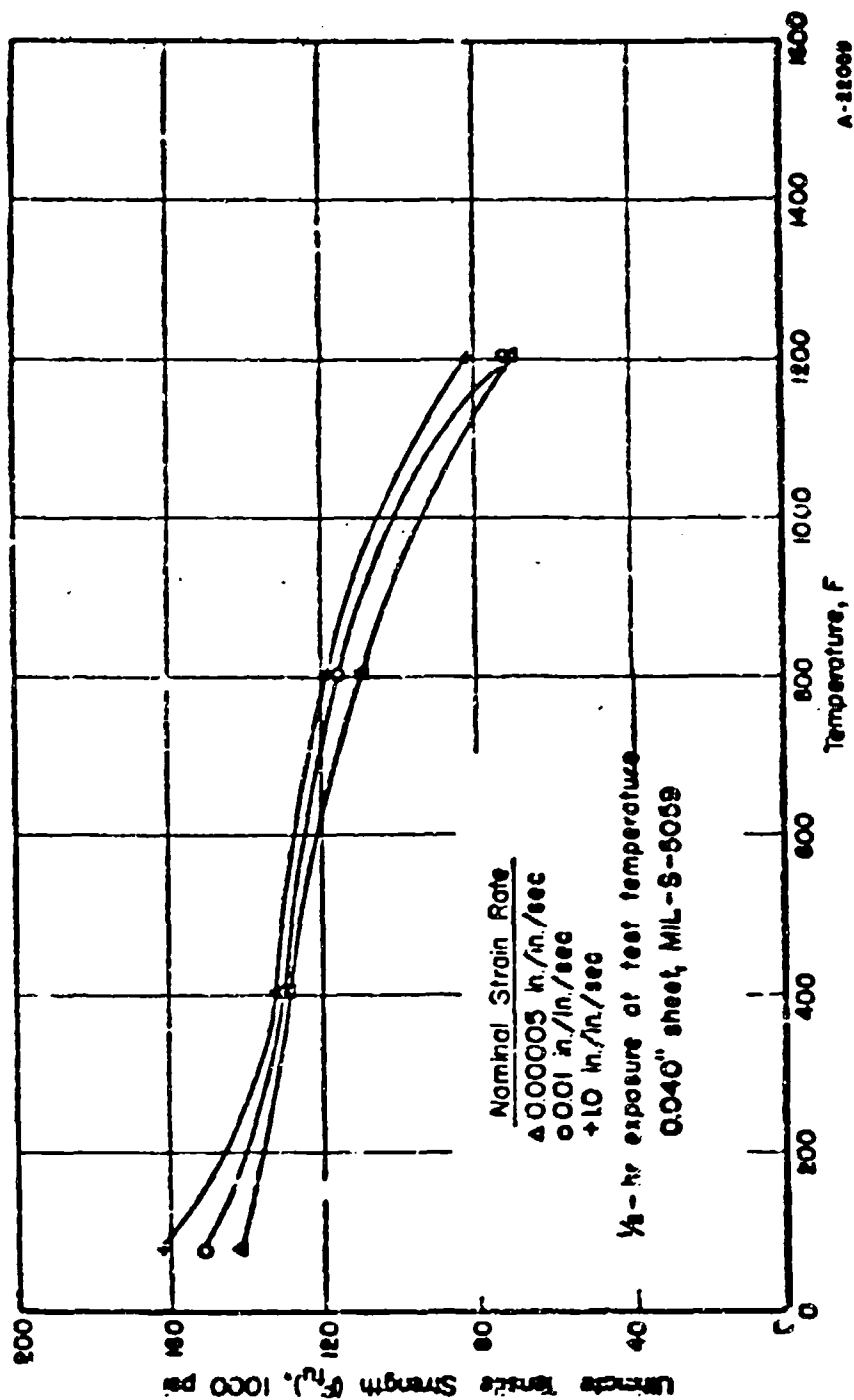


FIGURE 5. EFFECT OF STRAIN RATE ON THE TENSILE STRENGTH (F_T) OF AISI 301 (HALF HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. WADC 55-199, Part 2, p 53.

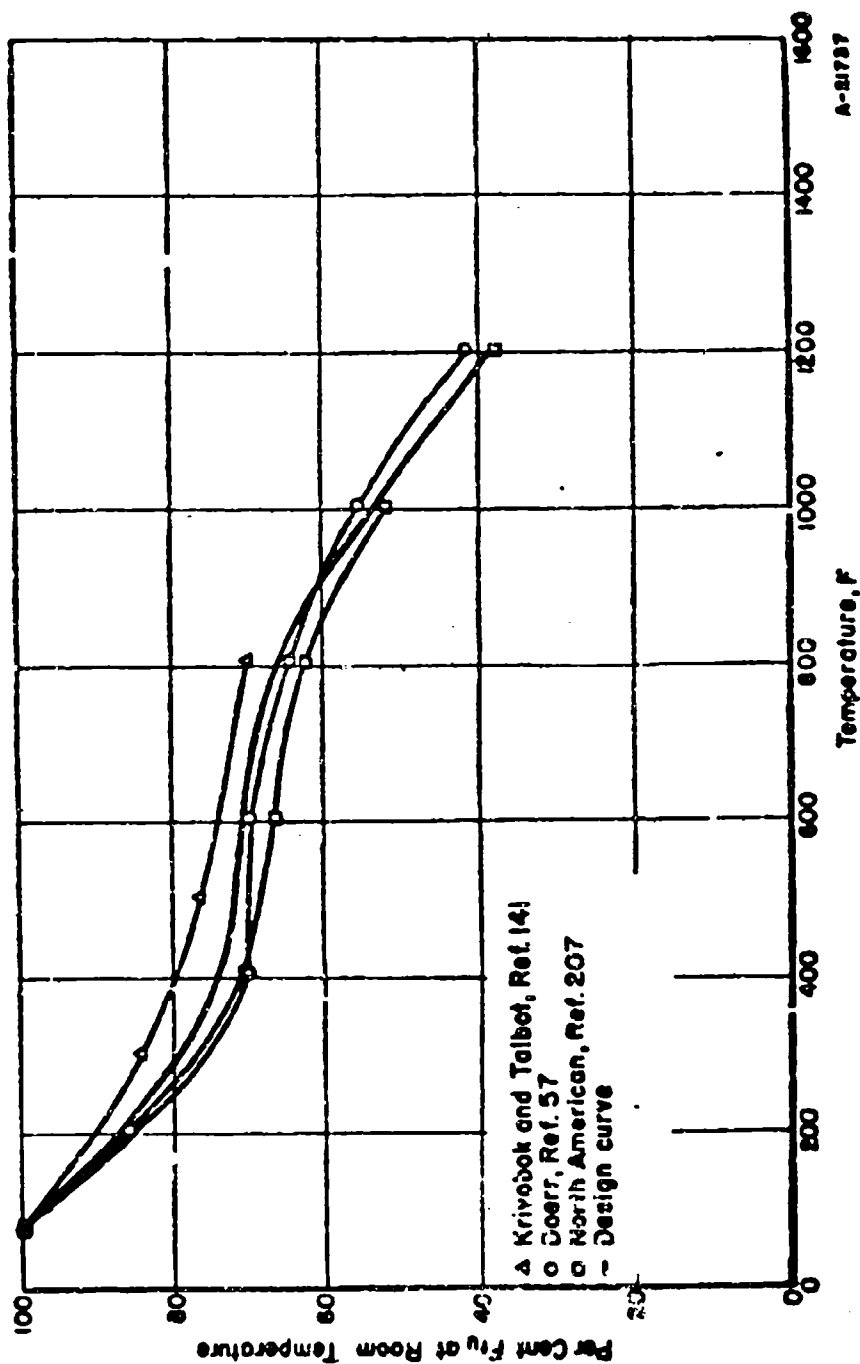


FIGURE 6. TENSILE STRENGTH (F_m), EXPRESSED AS A PERCENTAGE OF ROOM-TEMPERATURE TENSILE STRENGTH, OF AISI 301 (HALF HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE

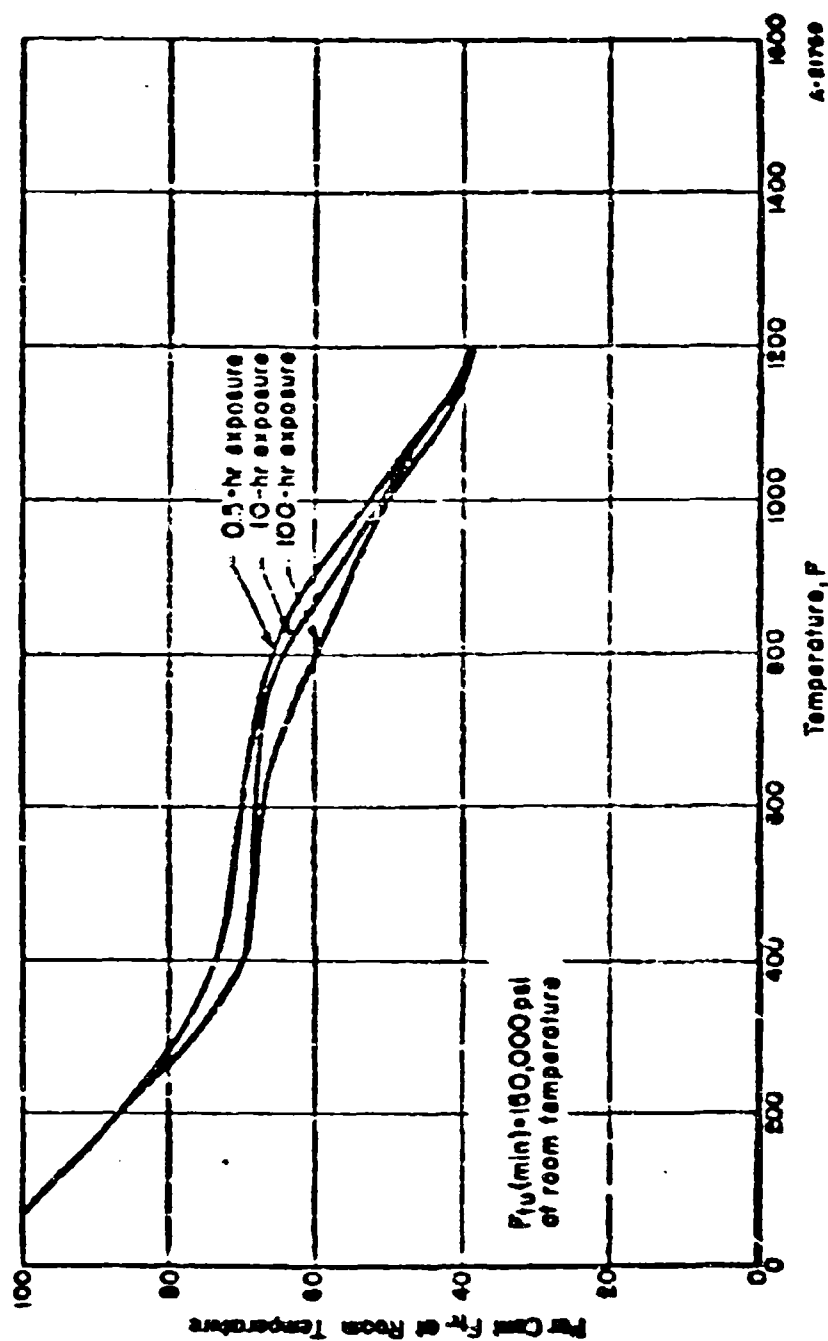


FIGURE 7. DESIGN CURVE FOR TENSILE STRENGTH (F_T) OF AISI 301 (HALF HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 57, 141, 207.

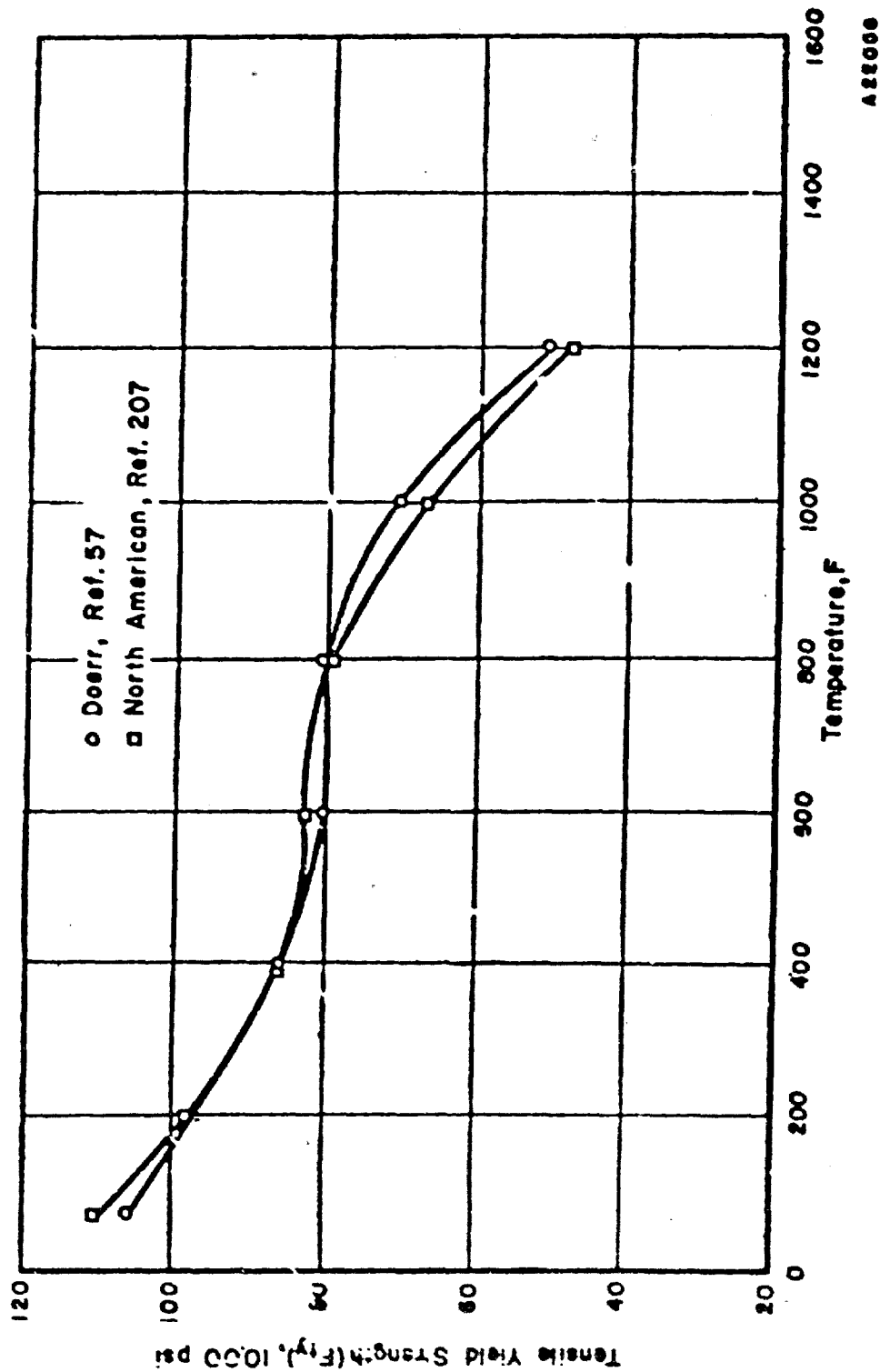


FIGURE 8. TENSILE YIELD STRENGTH (F_y) OF AISI 301 (HALF HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE

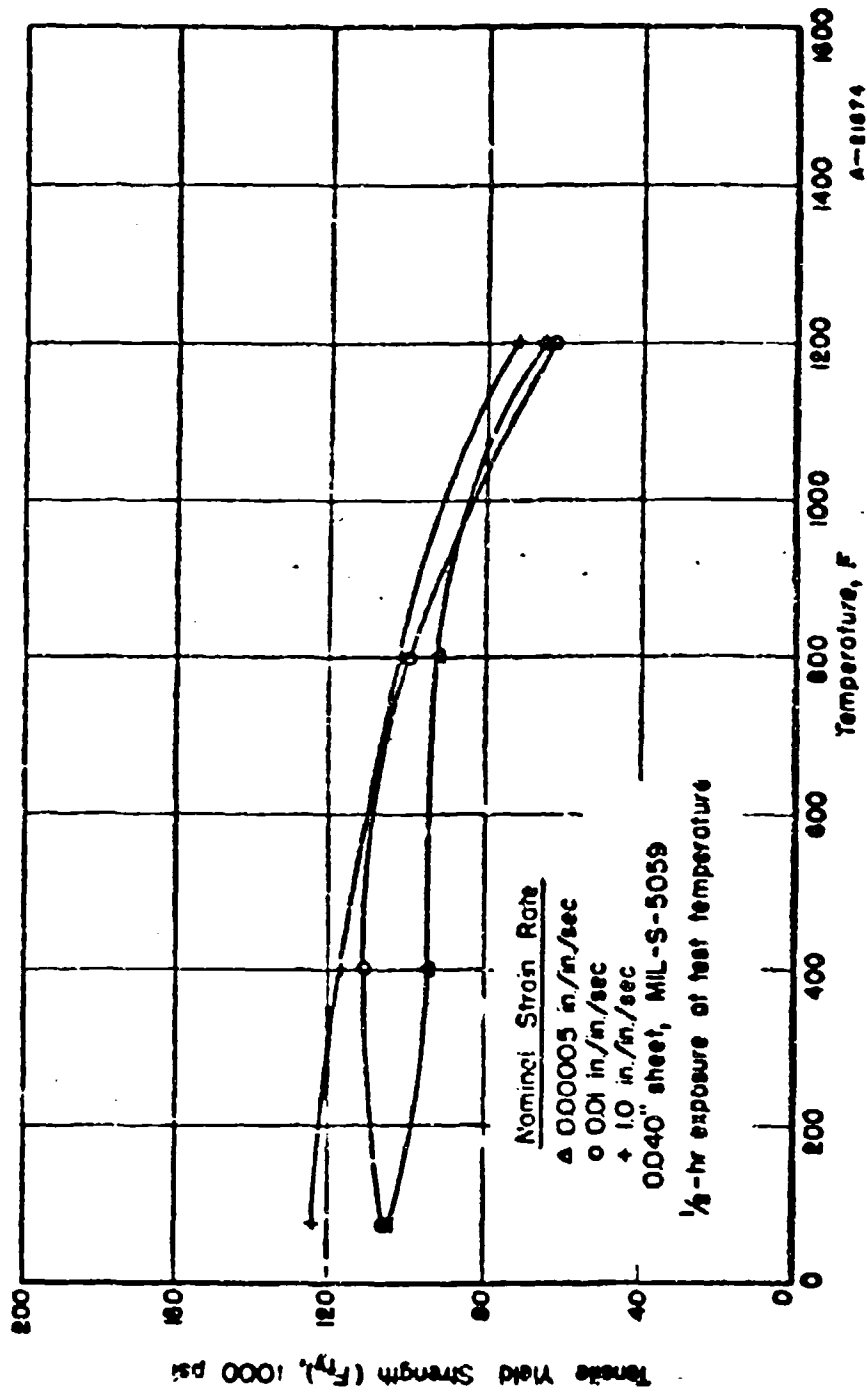


FIGURE 9. EFFECT OF STRAIN RATE ON THE TENSILE YIELD STRENGTH (F_{ty}) OF AISI 301 (HALF HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. WADC 55-199, Part 2, p 53.

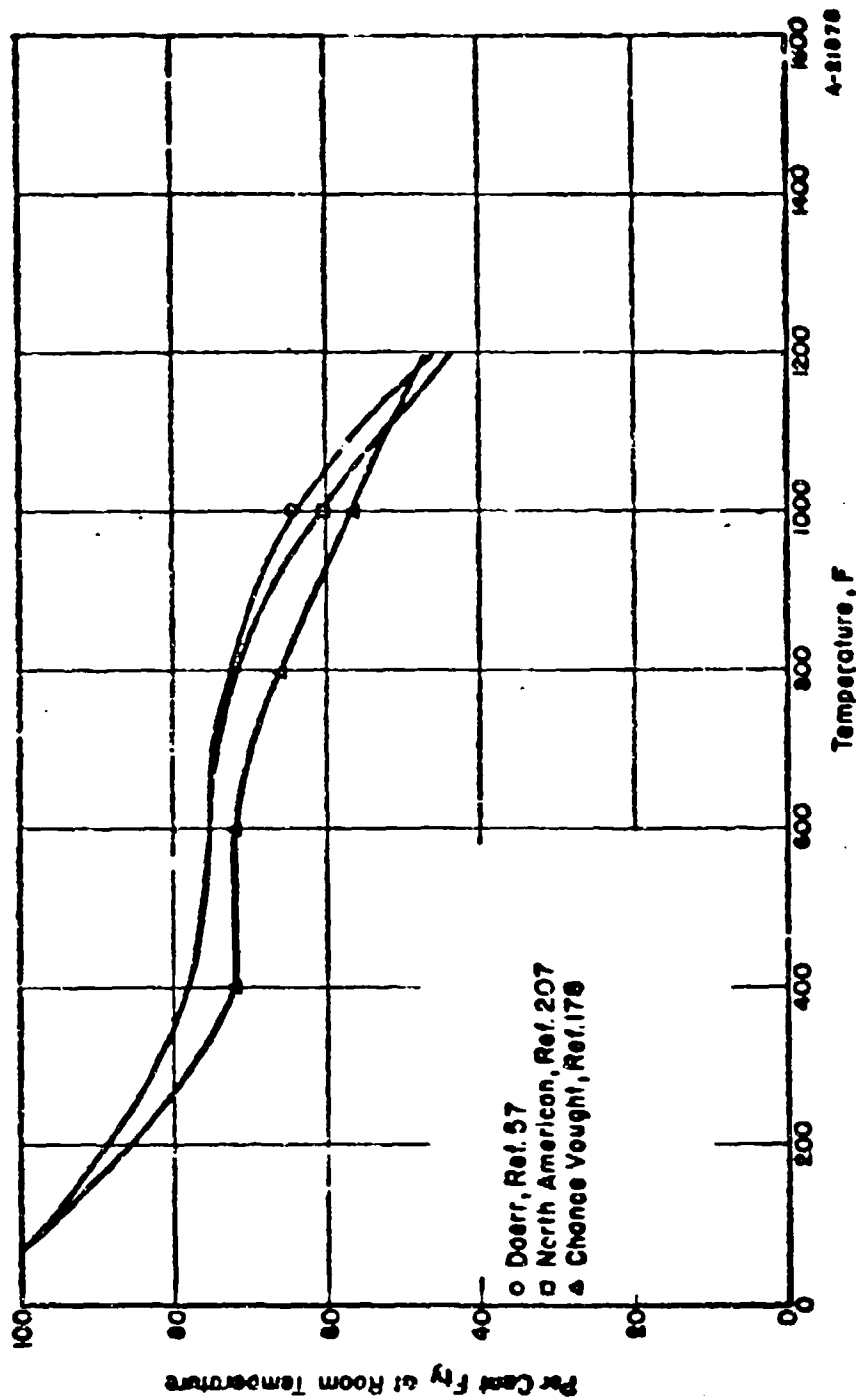


FIGURE 10. TENSILE YIELD STRENGTH (F_y) OF AISI 301 (HALF HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE
Ref. 57, 178, 207.

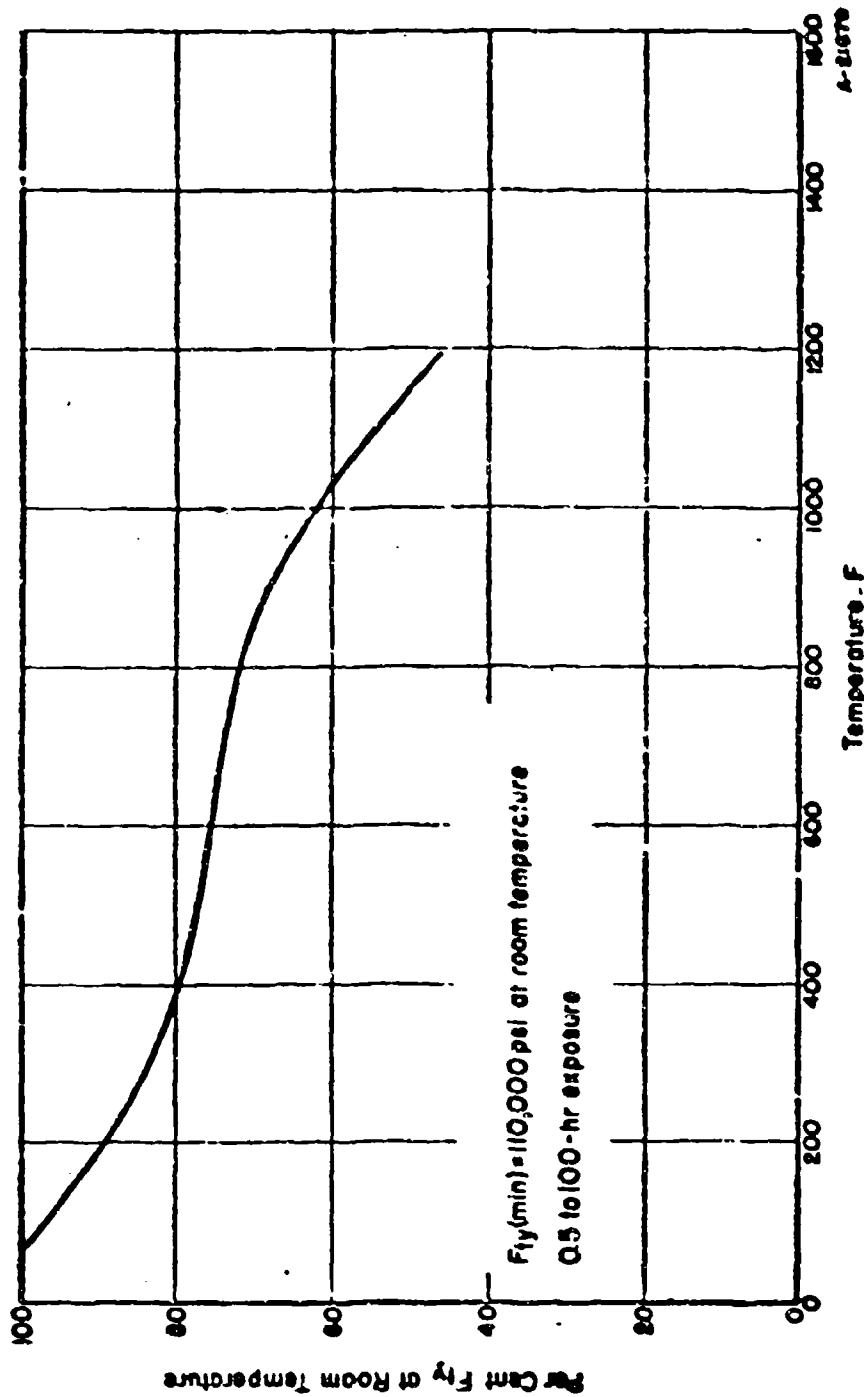


FIGURE 11. DESIGN CURVE FOR TENSILE YIELD STRENGTH (F_y) OF AISI 301 (HALF HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 57, 141, 207.

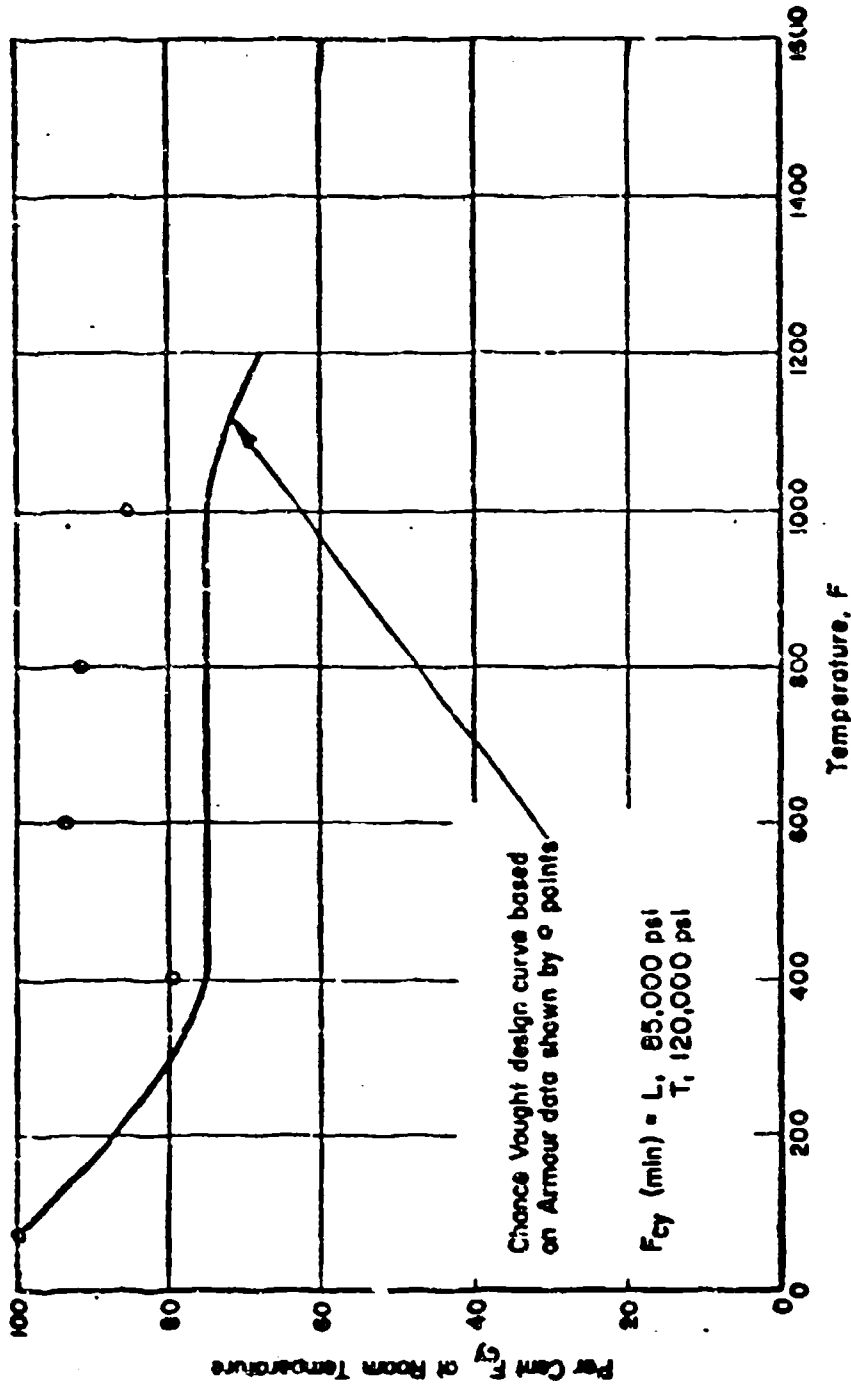


FIGURE 12. COMPRESSIVE YIELD STRENGTH (F_{cy}) EXPRESSED AS A PERCENTAGE OF ROOM-TEMPERATURE COMPRESSIVE YIELD STRENGTH OF AISI 301 (HALF HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 178.

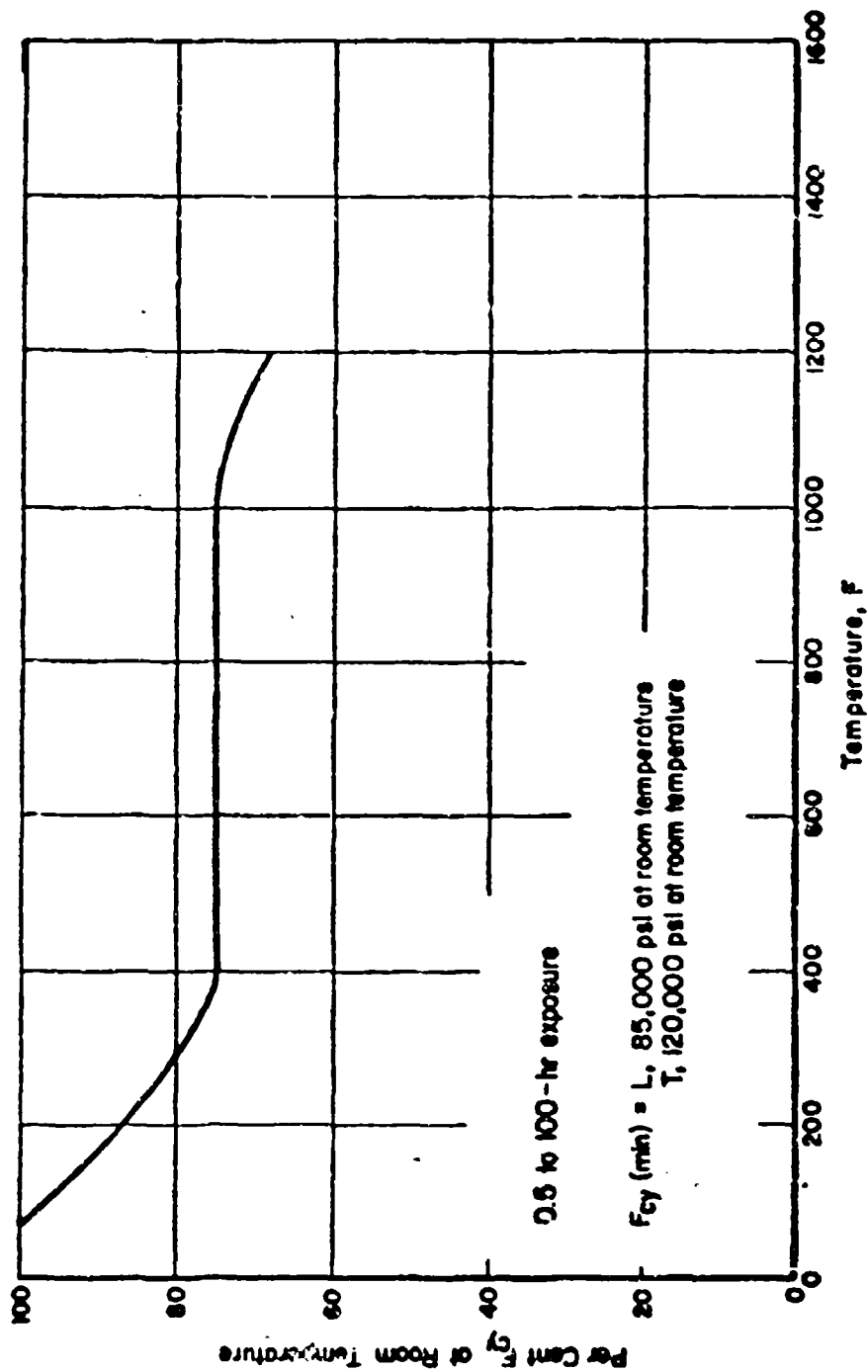


FIGURE 13. DESIGN CURVE FOR COMPRESSIVE YIELD STRENGTH (F_{cy}) OF AISI 301 (HALF HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 57, 176.

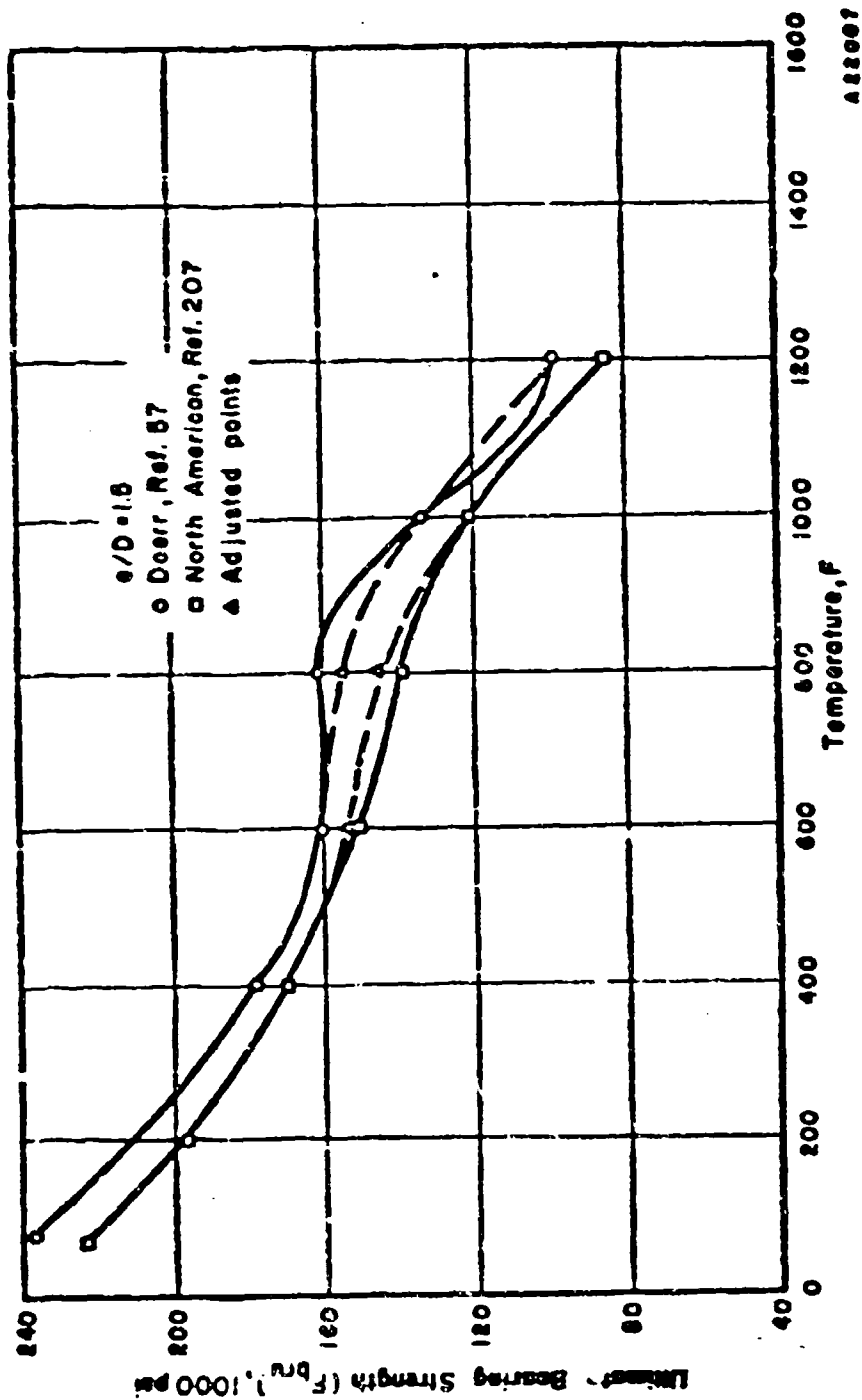


FIGURE 14. BEARING STRENGTH (F_b) OF AISI 301 (HALF HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE

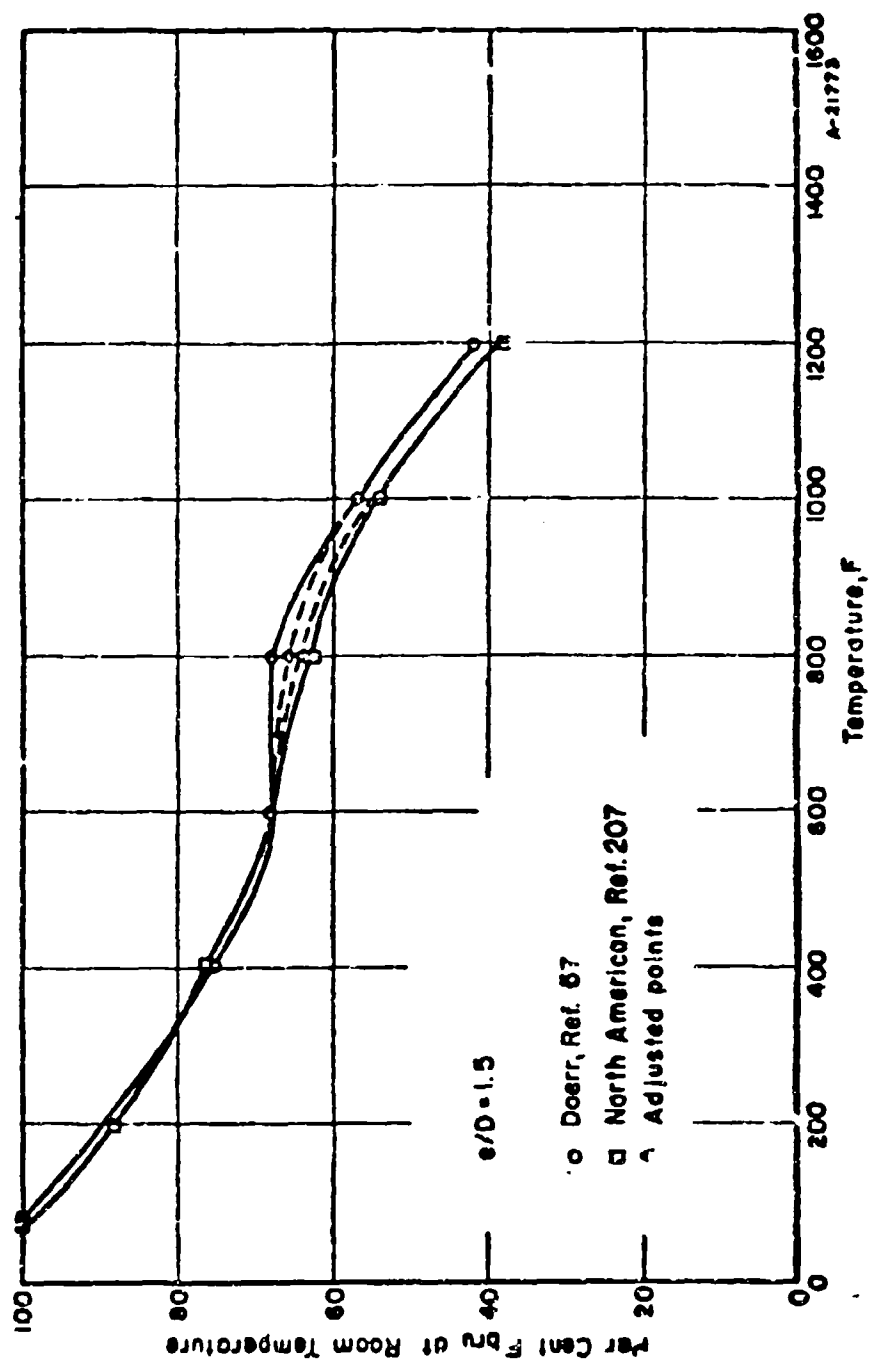


FIGURE 15. BEARING STRENGTH (F_{bru}) EXPRESSED AS A PERCENTAGE OF ROOM-TEMPERATURE BEARING STRENGTH OF AISI 301 (HALF HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE.

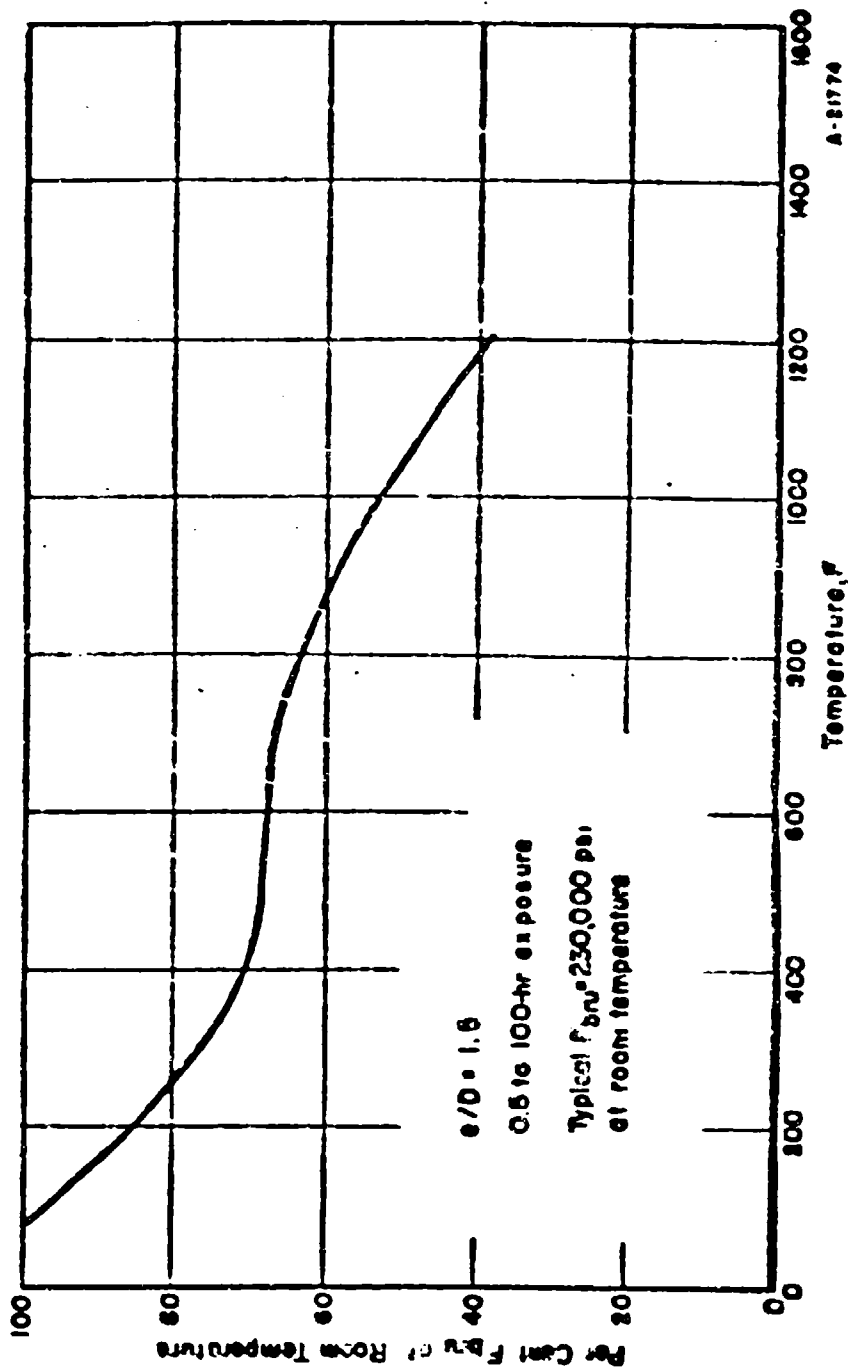


FIGURE 16. DESIGN CURVE FOR BEARING STRENGTH (F_{brd}) OF AISI 301 (HALF HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 57, 207.

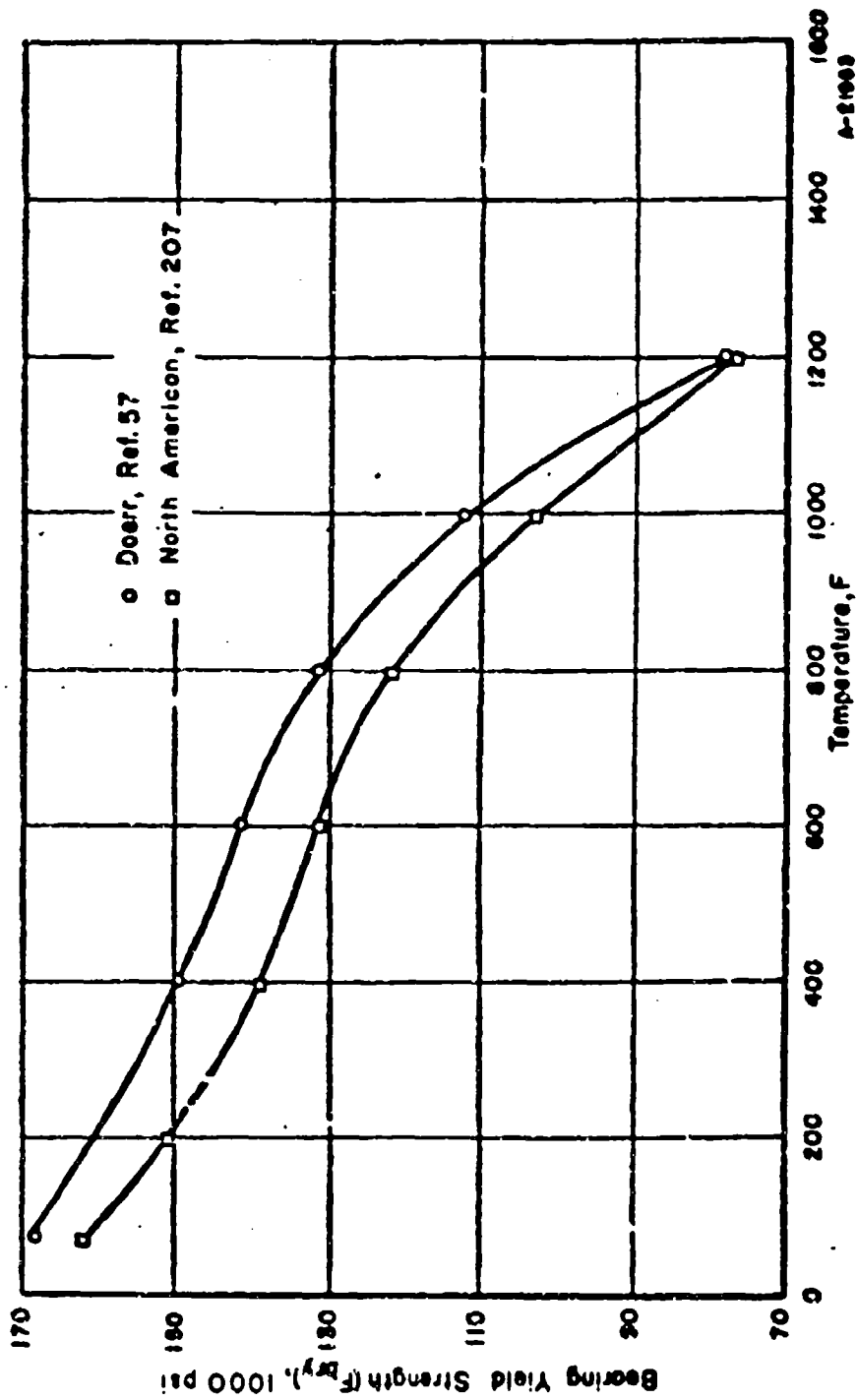


FIGURE 17. BEARING YIELD STRENGTH (F_{by}) OF AISI 301 (HALF HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE

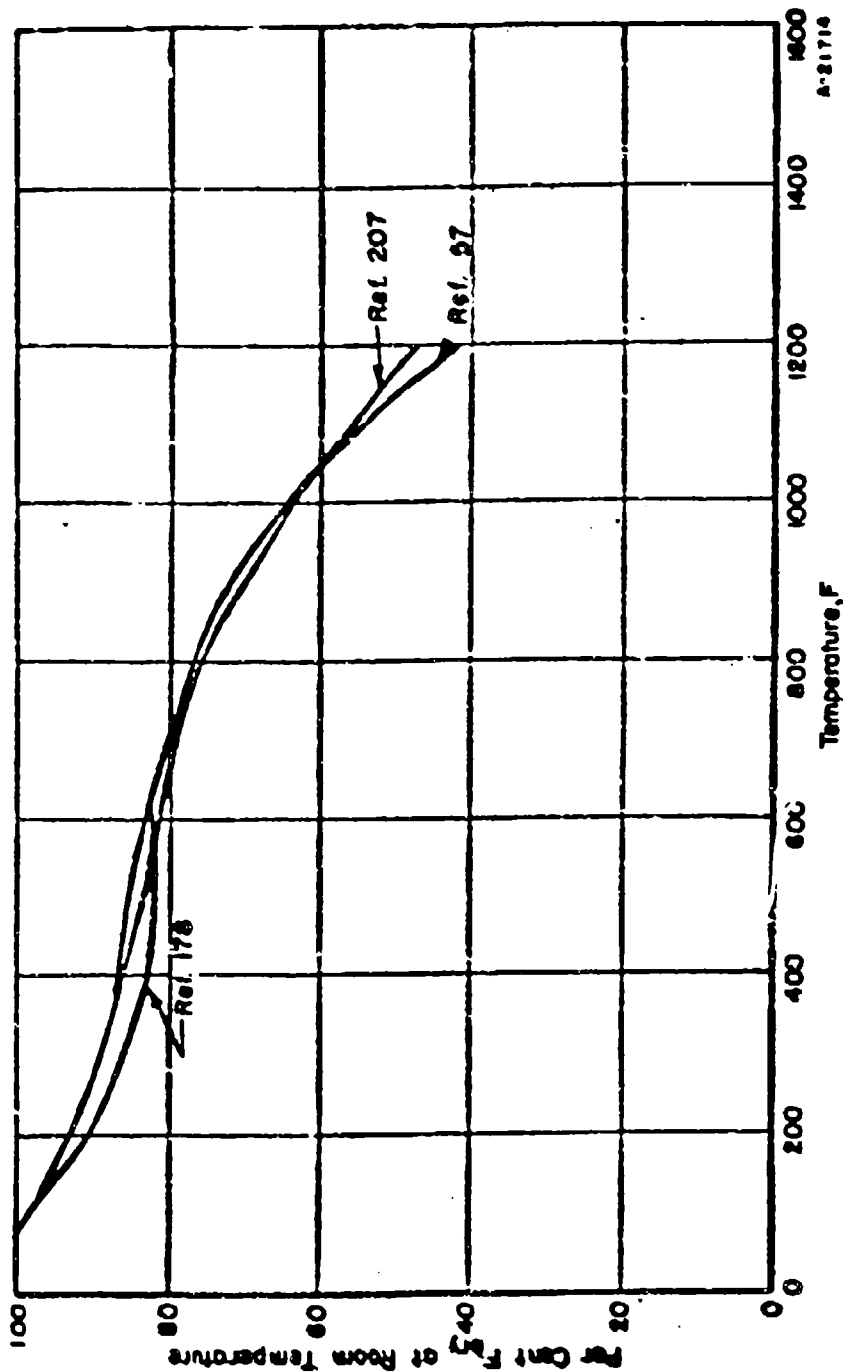


FIGURE 18. BEARING YIELD STRENGTH (F_{by}) EXPRESSED AS A PERCENTAGE OF ROOM-TEMPERATURE BEARING YIELD STRENGTH OF AISI 301 (HALF HARD) STAIN-LESS STEEL AT ELEVATED TEMPERATURE

Ref. 57, 178, 207.

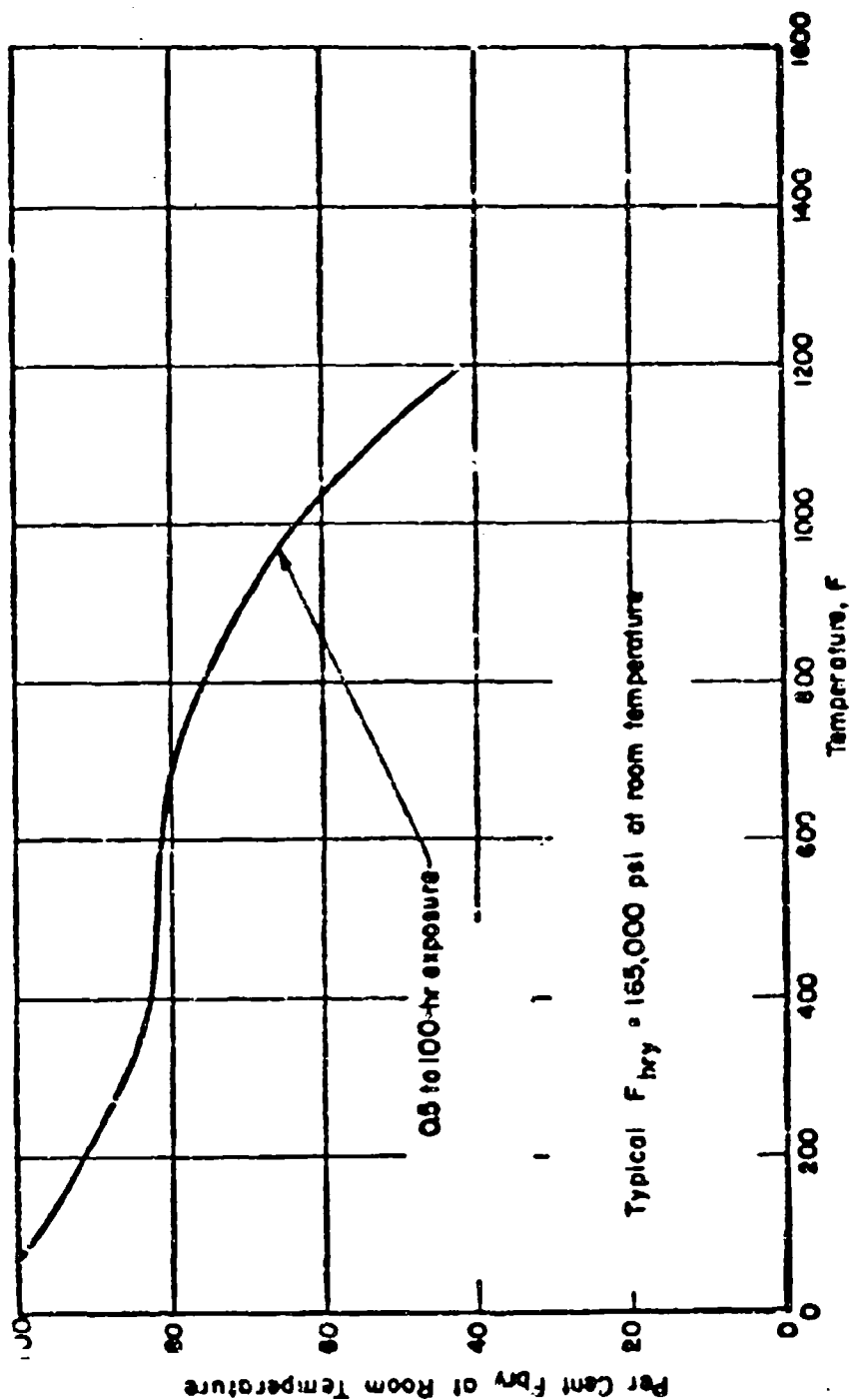


FIGURE 19. DESIGN CURVE FOR BEARING YIELD STRENGTH (F_{bry}) OF AISI 301 (HALF HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 97, 141, 207.

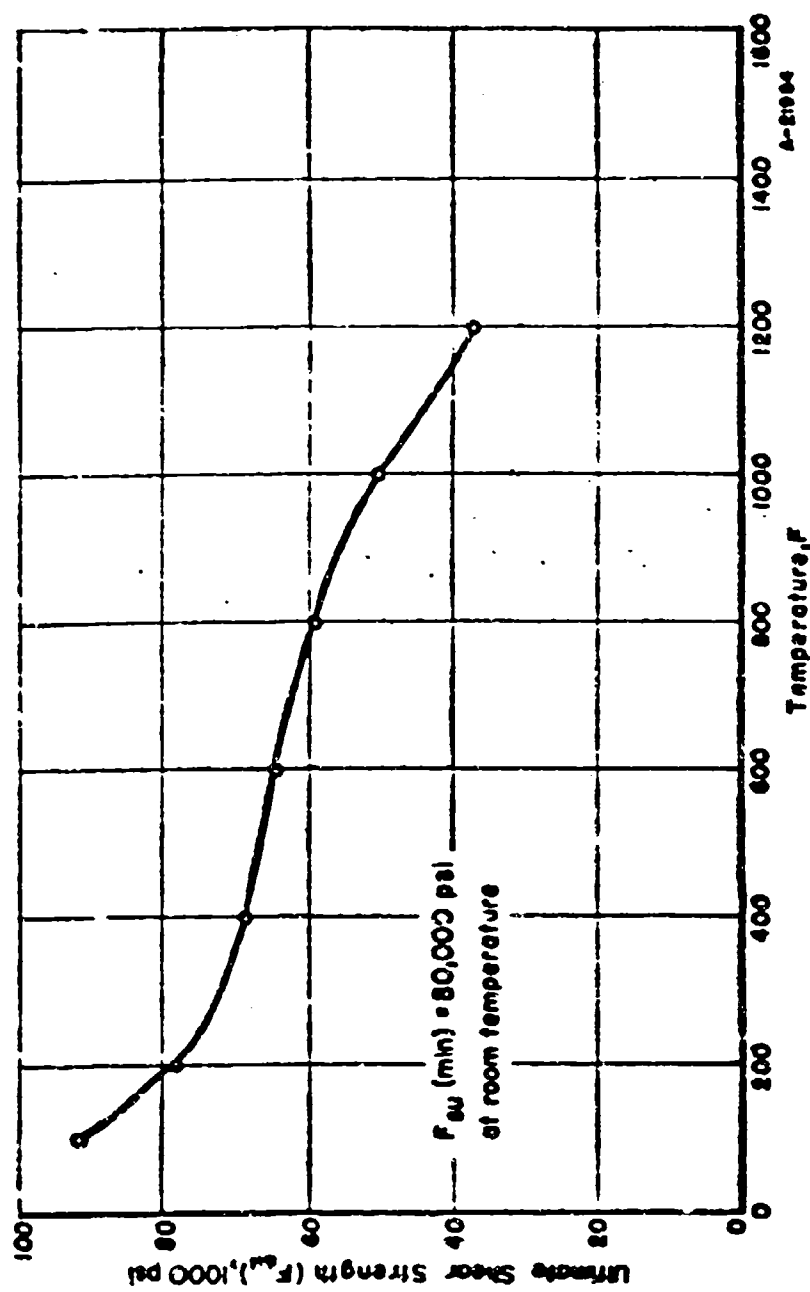


FIGURE 20. SHEAR STRENGTH (F_{su}) OF AISI 301 (HALF HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 207, 178.

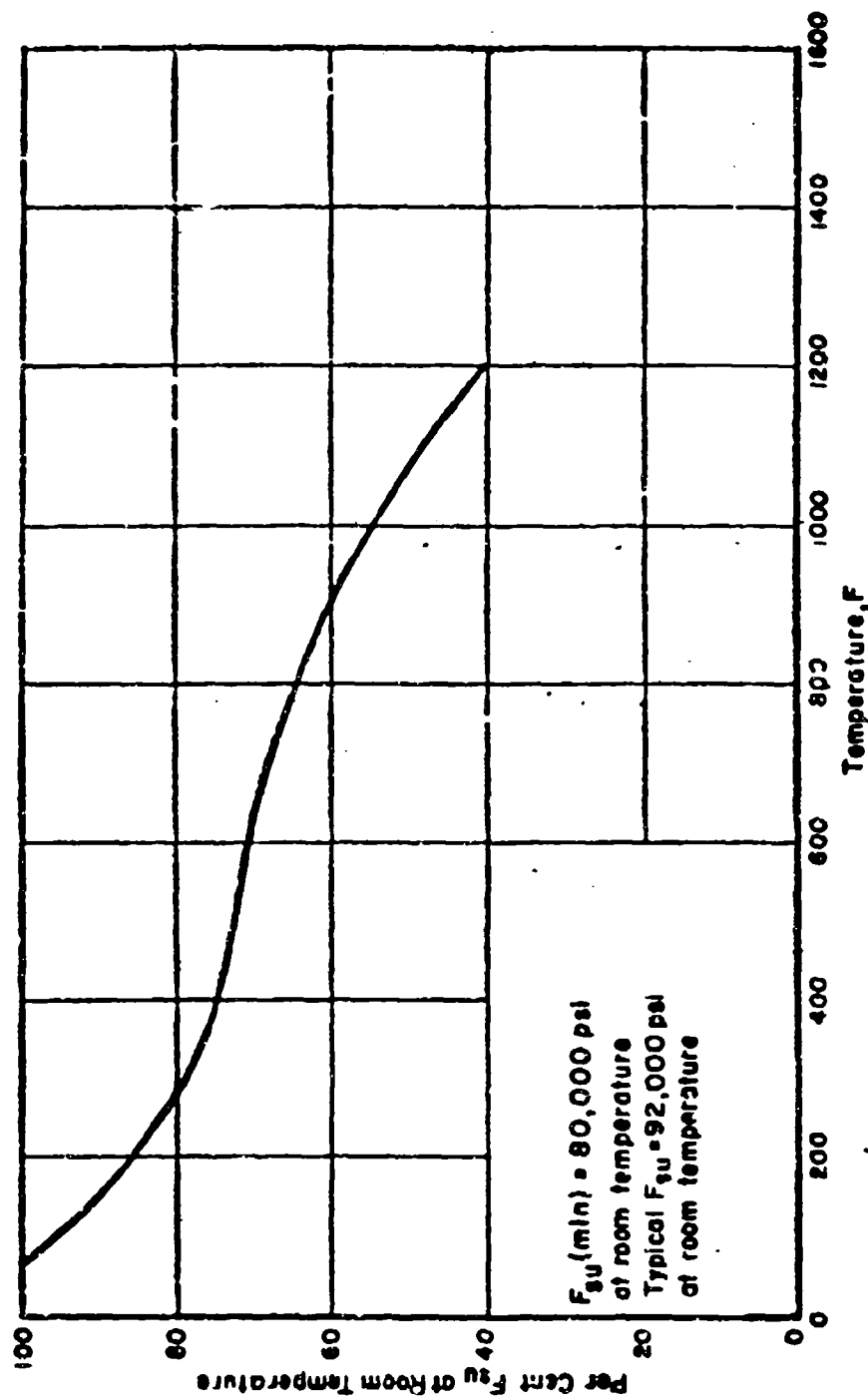


FIGURE 21. DESIGN CURVE FOR SHEAR STRENGTH (F_{su}) OF AISI 301 (HALF HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 207.

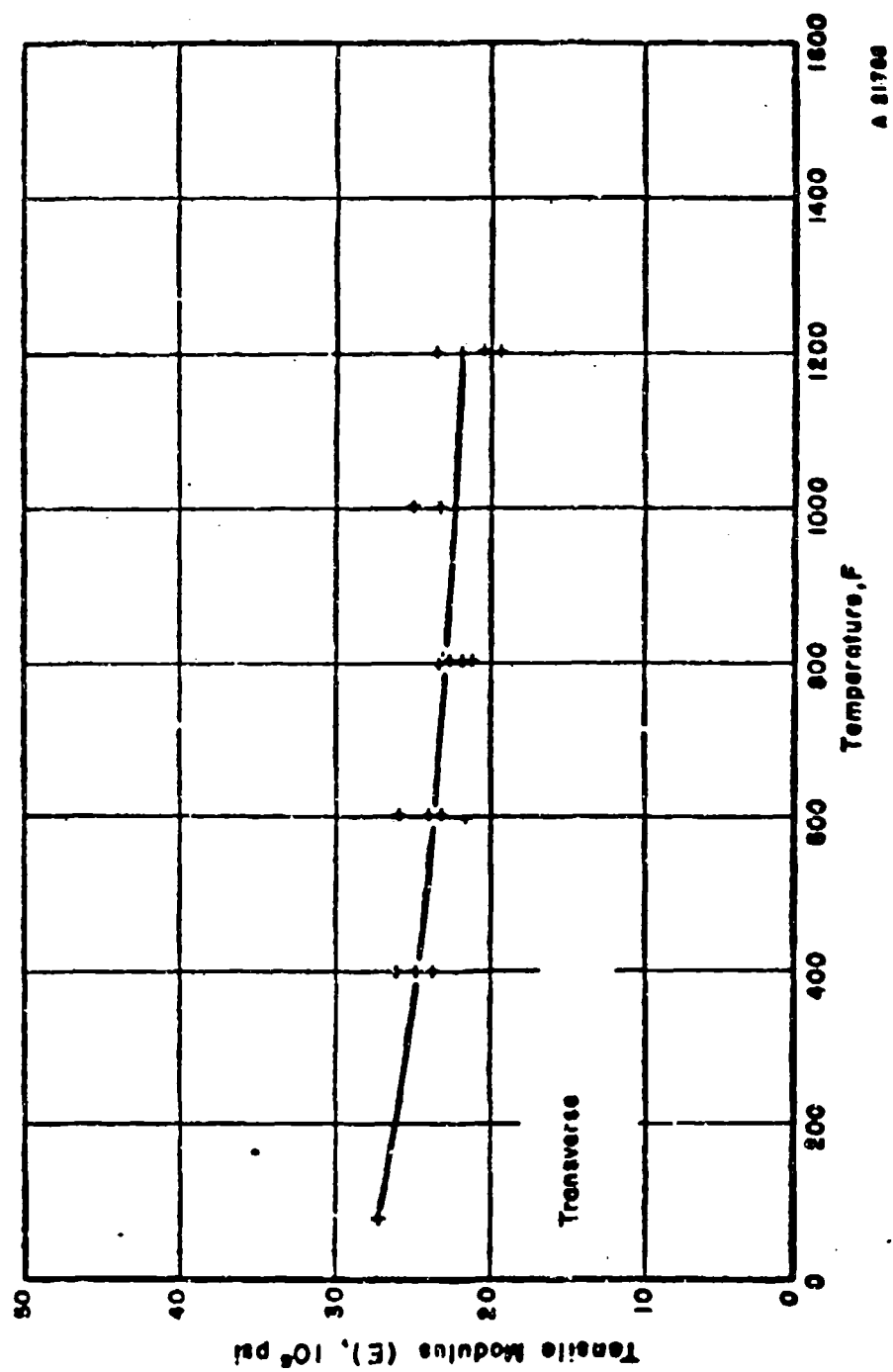


FIGURE 22. TENSILE MODULUS (E) OF AISI 301 (HALF HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 57.

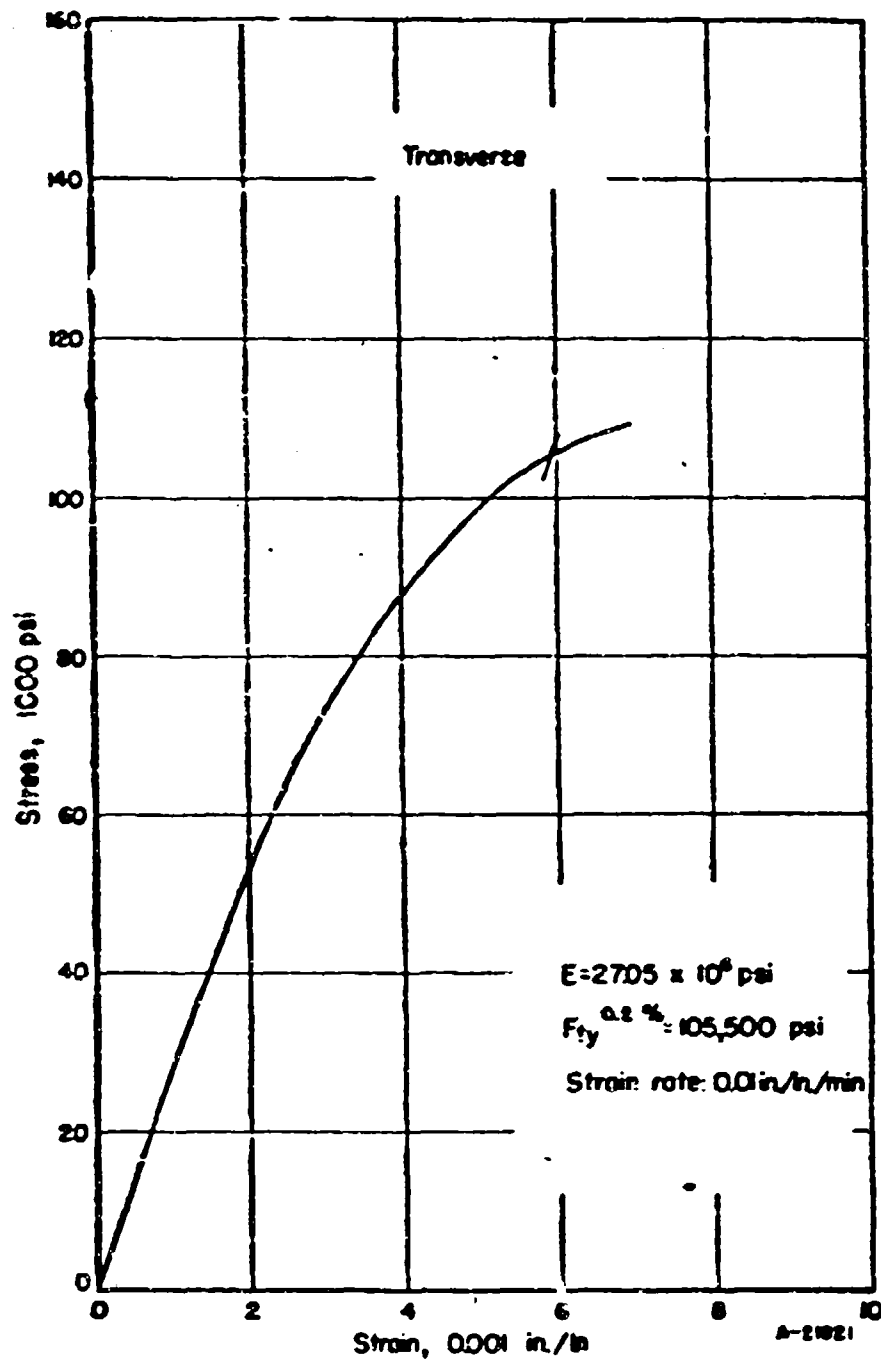


FIGURE 23. TENSILE STRESS-STRAIN CURVE FOR AISI 301 (HALF HARD) STAINLESS STEEL AT ROOM TEMPERATURE

Ref. 57.

WADC TR 55-150 Pt 3

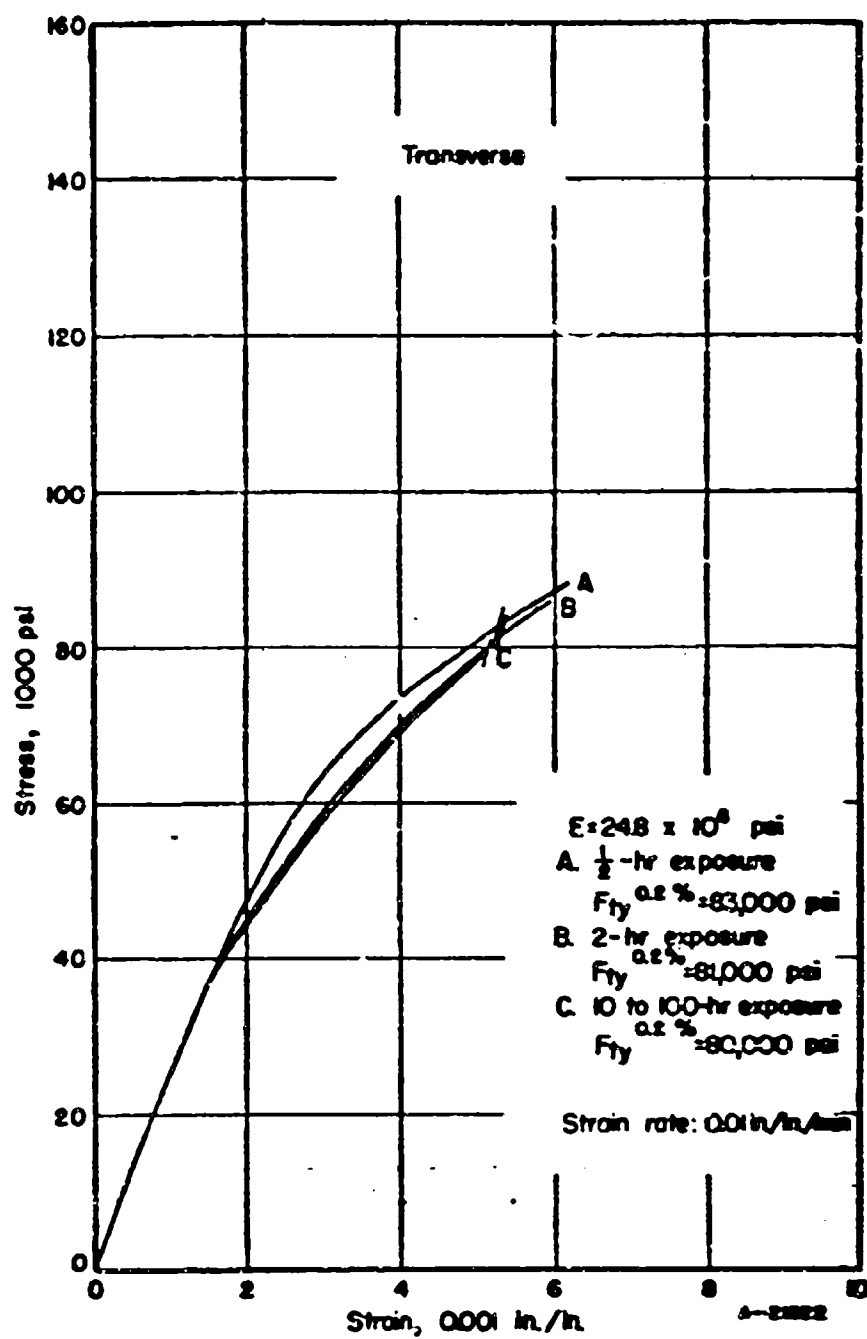


FIGURE 24. TENSILE STRESS-STRAIN CURVES FOR AISI 301 (HALF HARD) STAINLESS STEEL AT 400 F

Ref. 57.

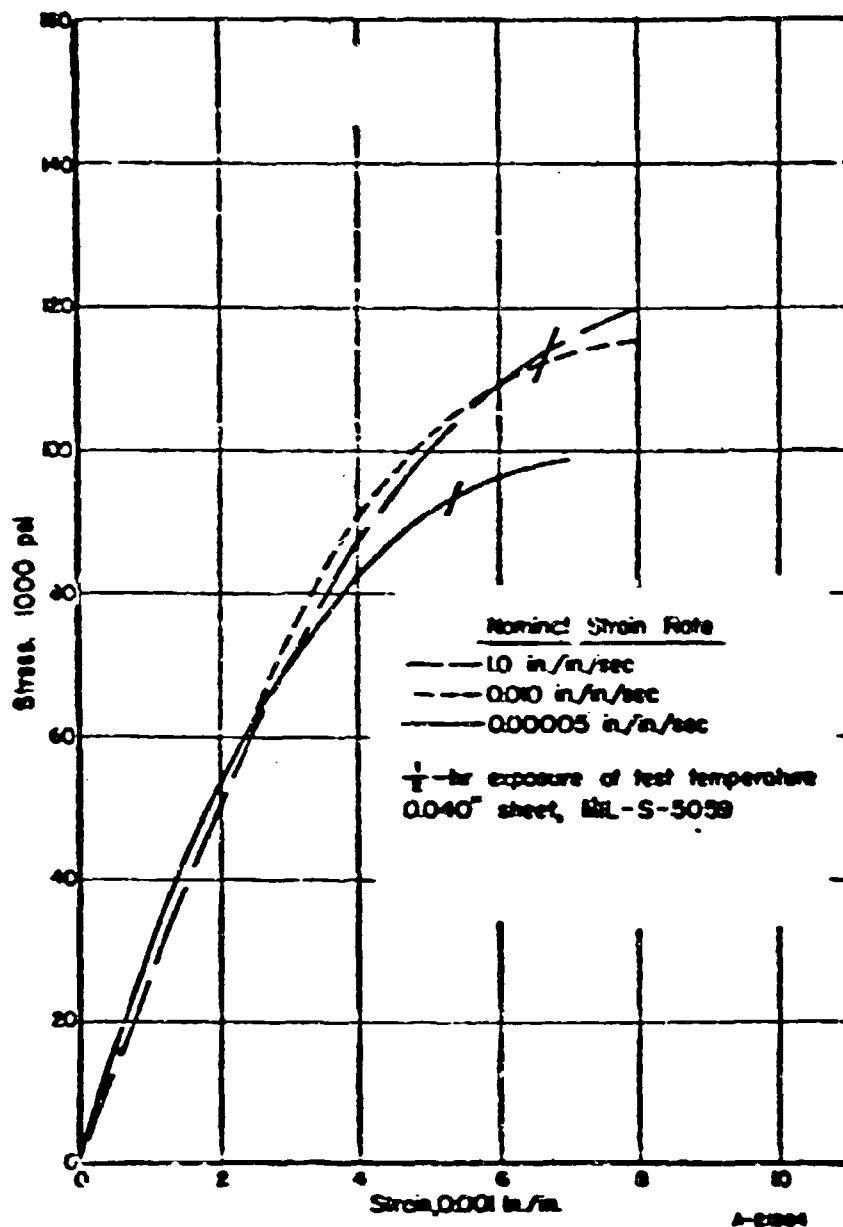


FIGURE 25. EFFECT OF STRAIN RATE ON THE TENSILE STRESS-STRAIN CURVE OF A51 301 (HALF HARD) STAINLESS STEEL AT 400°F

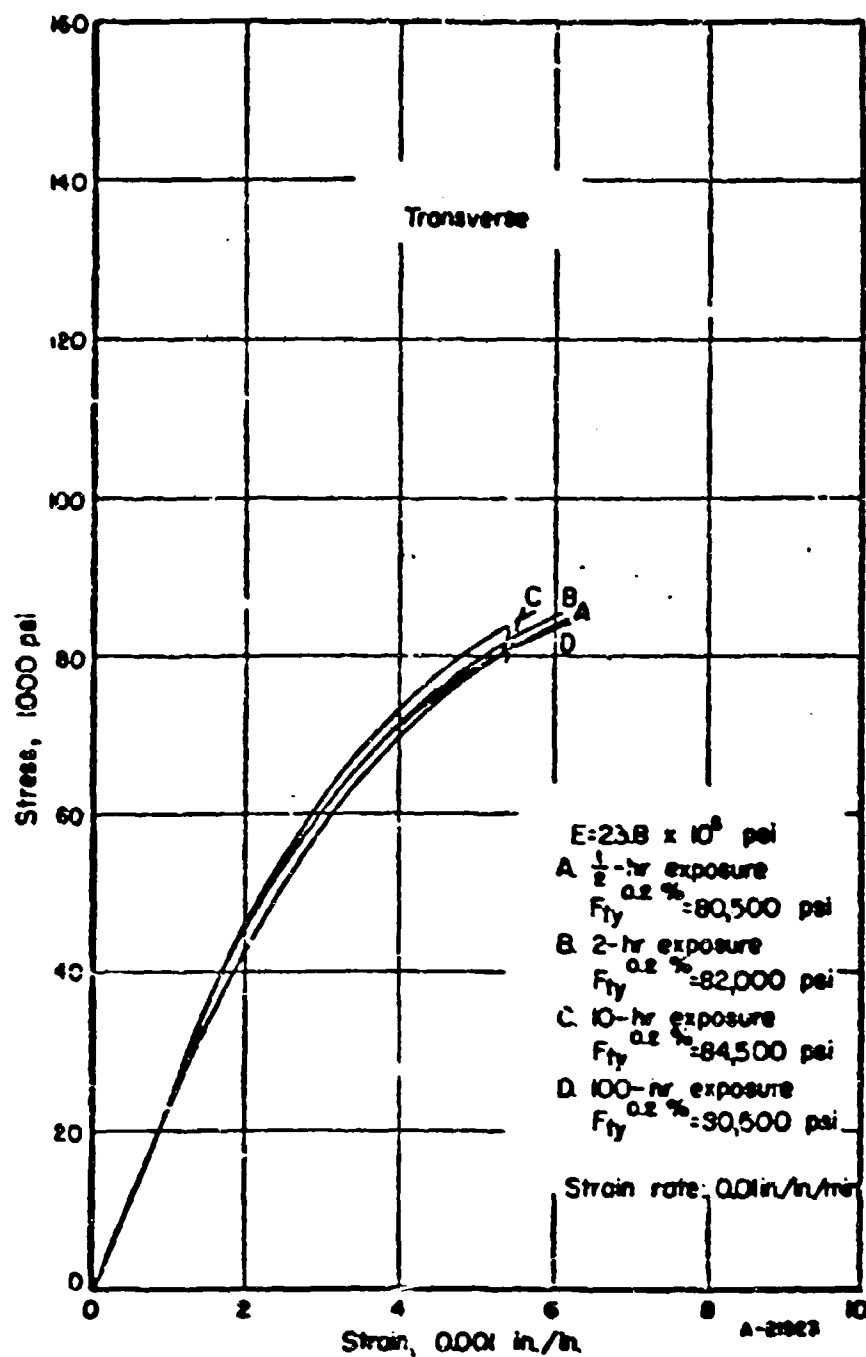


FIGURE 26. TENSILE STRESS-STRAIN CURVES FOR AISI 301 (HALF HARD) STAINLESS STEEL AT 600 F

Ref. 57.

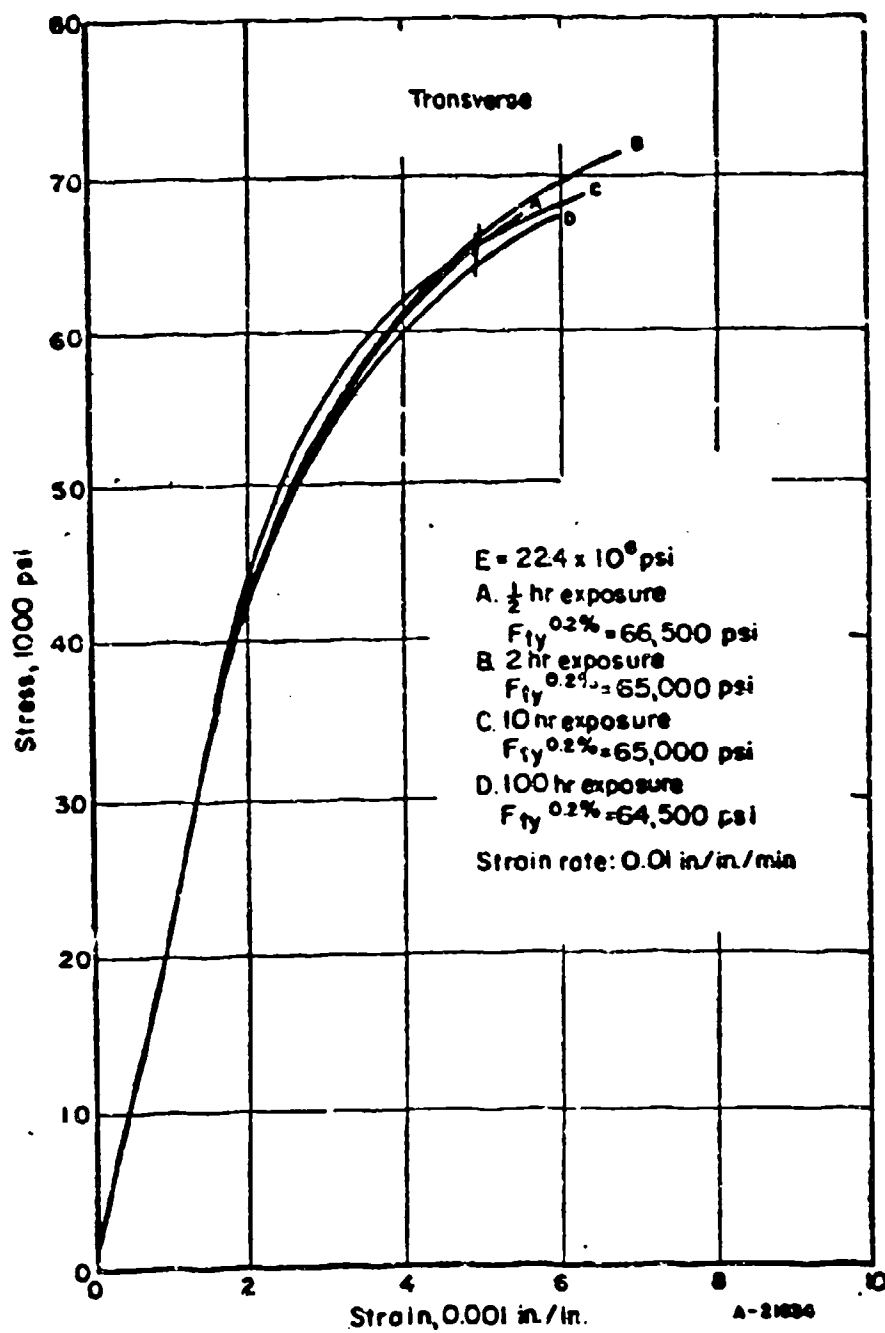


FIGURE 28. TENSILE STRESS-STRAIN CURVES FOR AISI 301 (HALF HARD) STAINLESS STEEL AT 1000 F

Ref. 57.

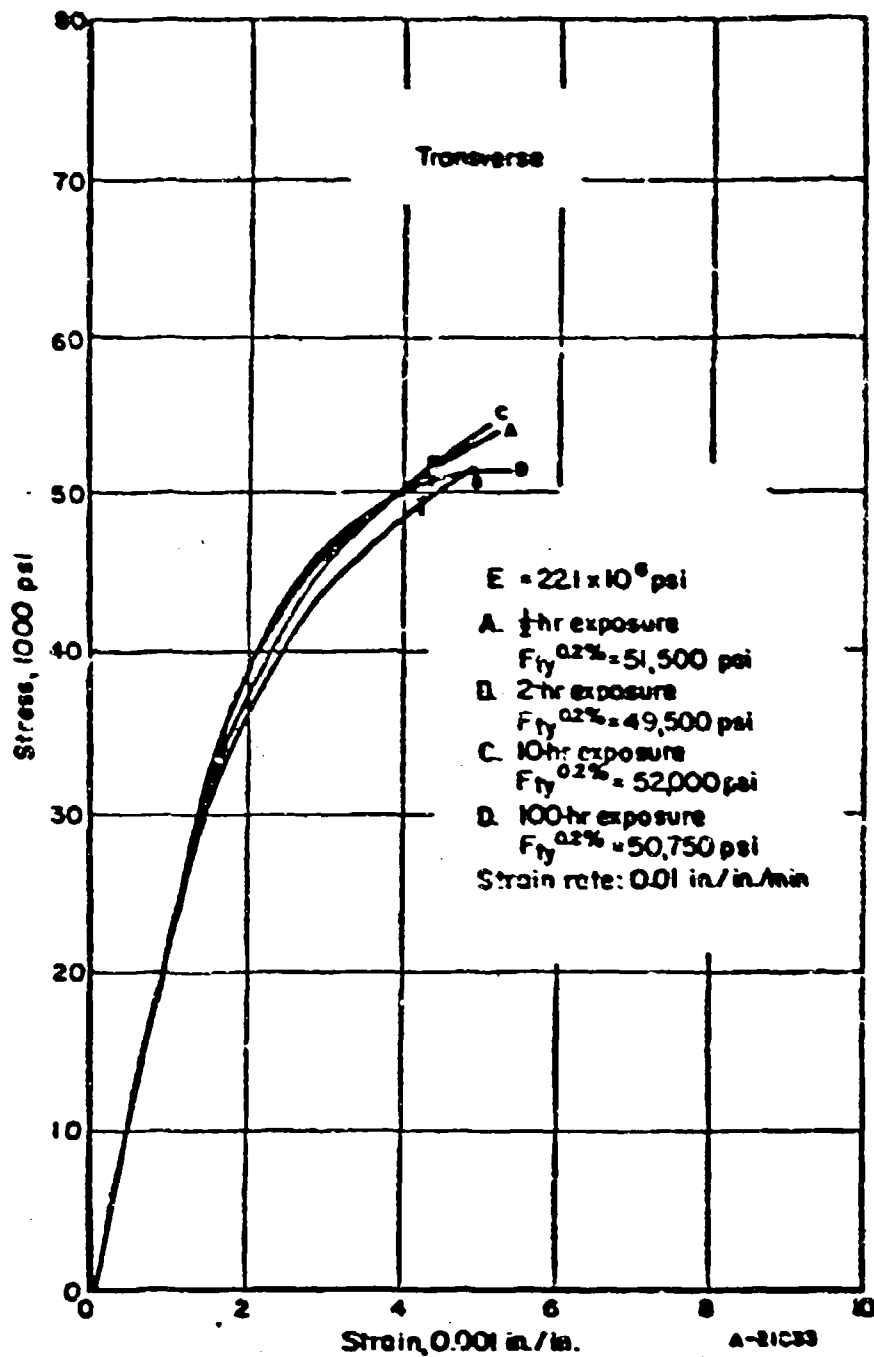
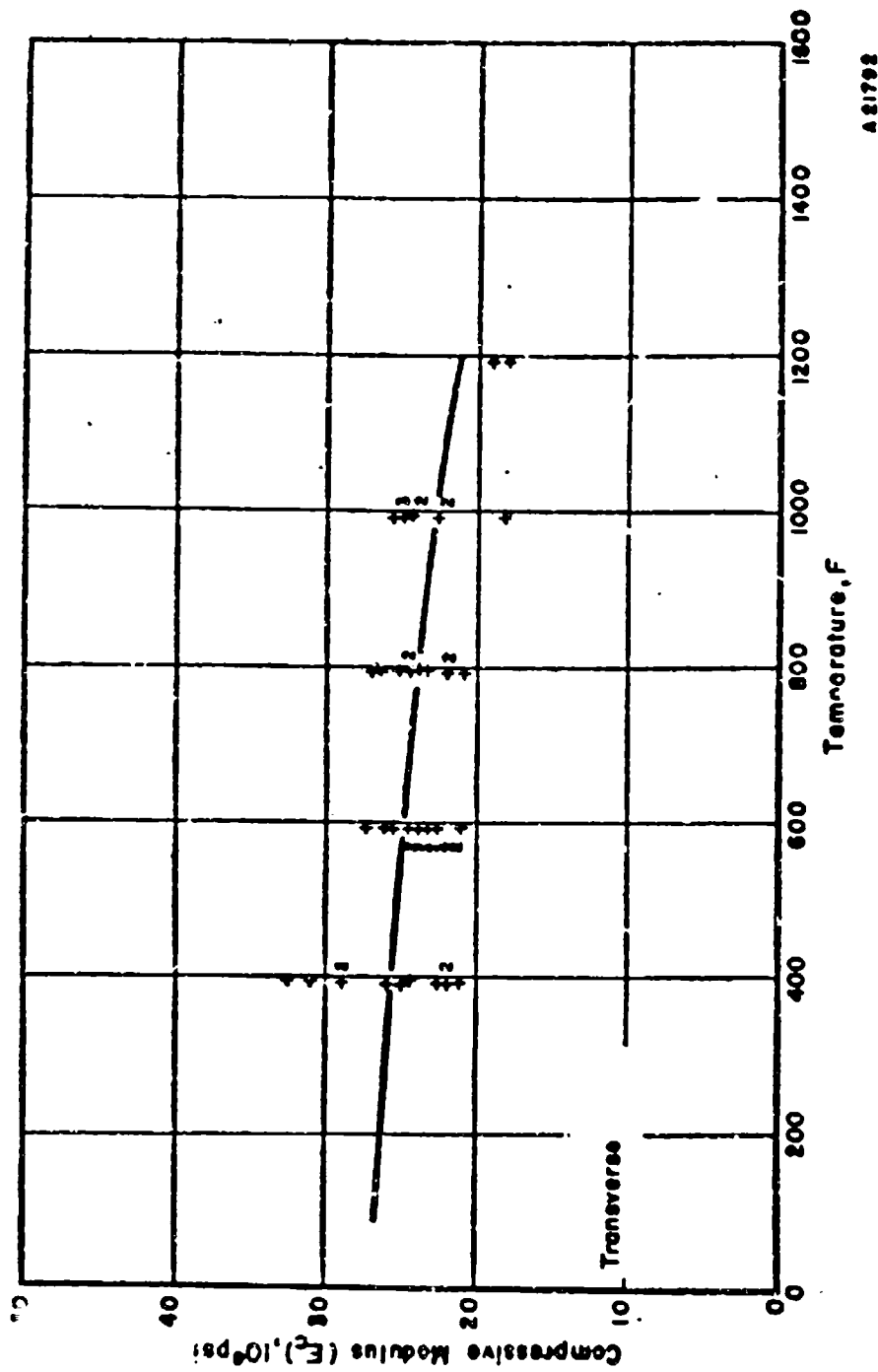


FIGURE 29. TENSILE STRESS-STRAIN CURVES FOR AISI 301 (HALF HARD) STAINLESS STEEL AT 1200 F

Ref. 57.

WADC TR 55-150 Pt 5



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FIGURE 30. COMPRESSIVE MODULUS (E_c) OF AISI 301 (HALF HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 57.

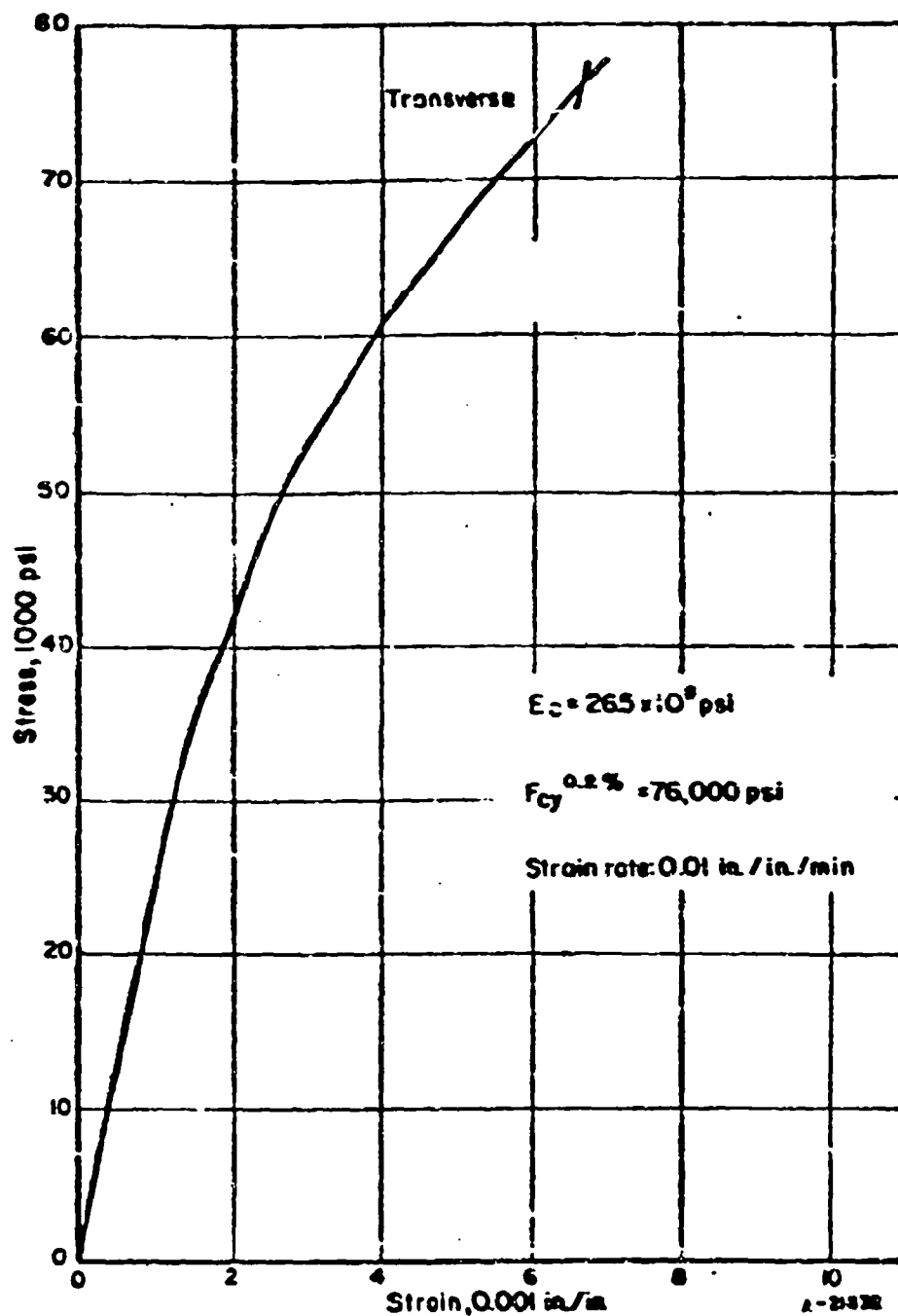


FIGURE 31. COMPRESSIVE STRESS-STRAIN CURVE FOR AISI 301 (HALF HARD) STAINLESS STEEL AT ROOM TEMPERATURE

Ref. 57.

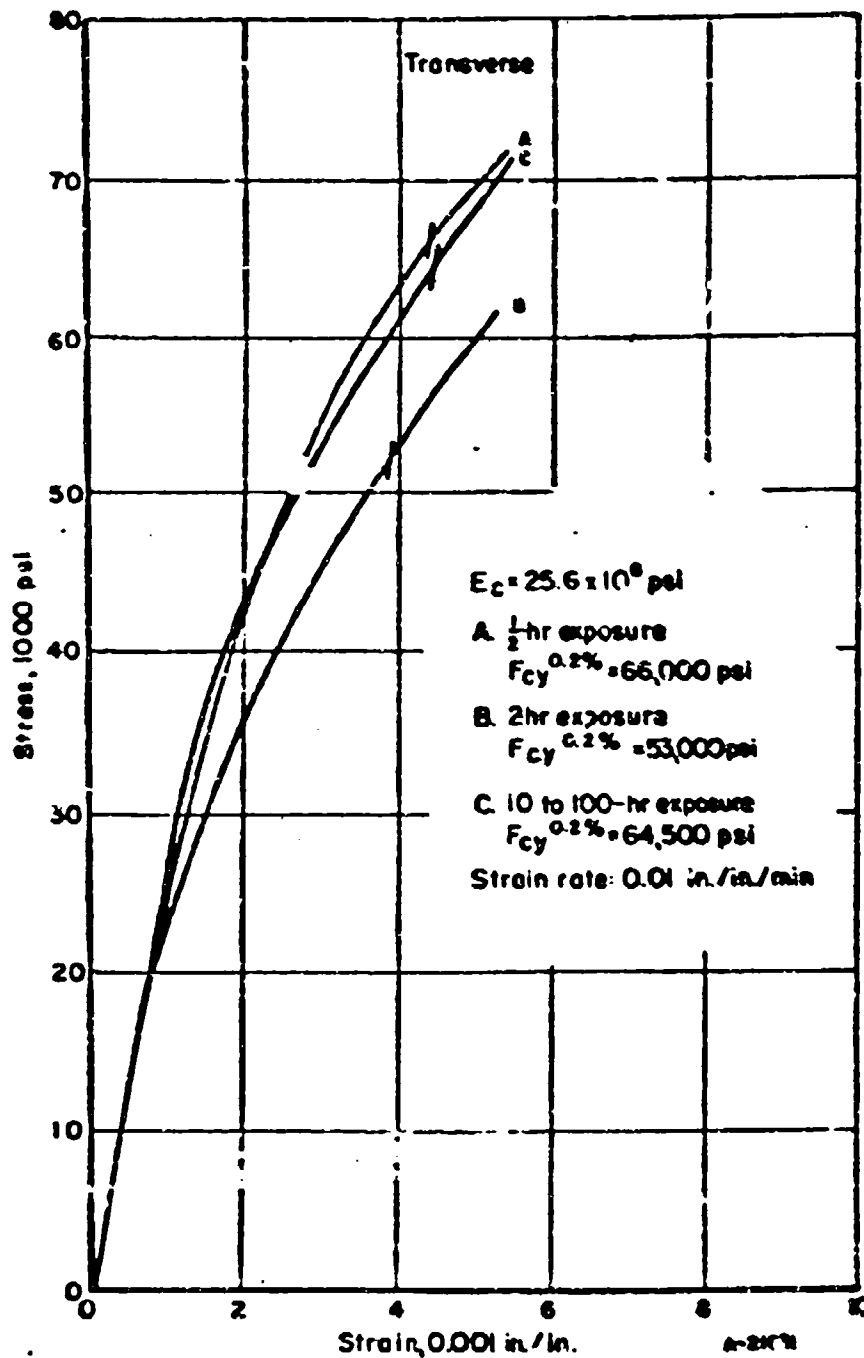


FIGURE 32. COMPRESSIVE STRESS-STRAIN CURVES FOR AISI 301 (HALF HARD) STAINLESS STEEL AT 400 F

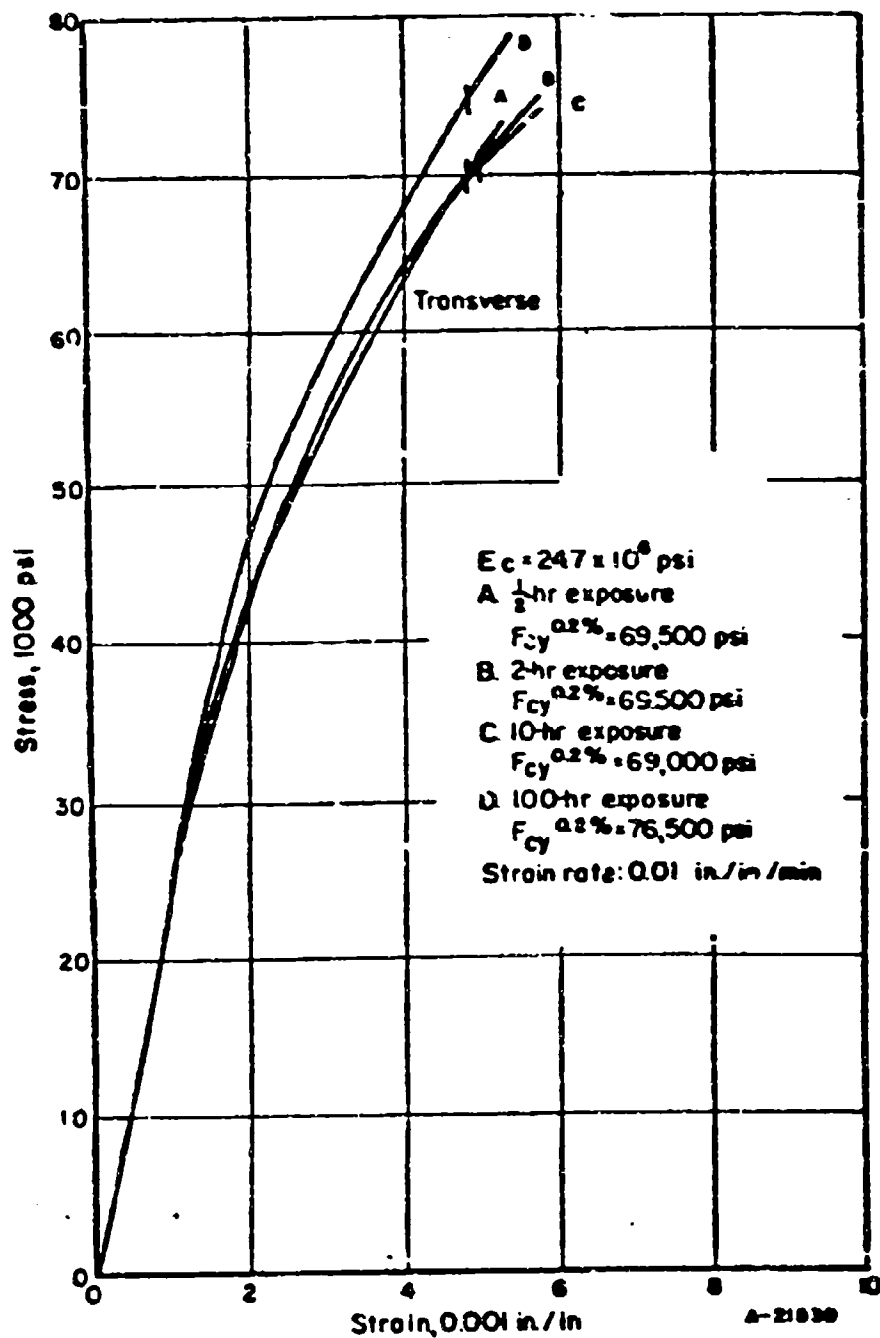


FIGURE 33. COMPRESSIVE STRESS-STRAIN CURVES FOR AISI 301 (HALF HARD) STAINLESS STEEL AT 600 F

Ref. 57.

WADC TR 55-150 Pt 5

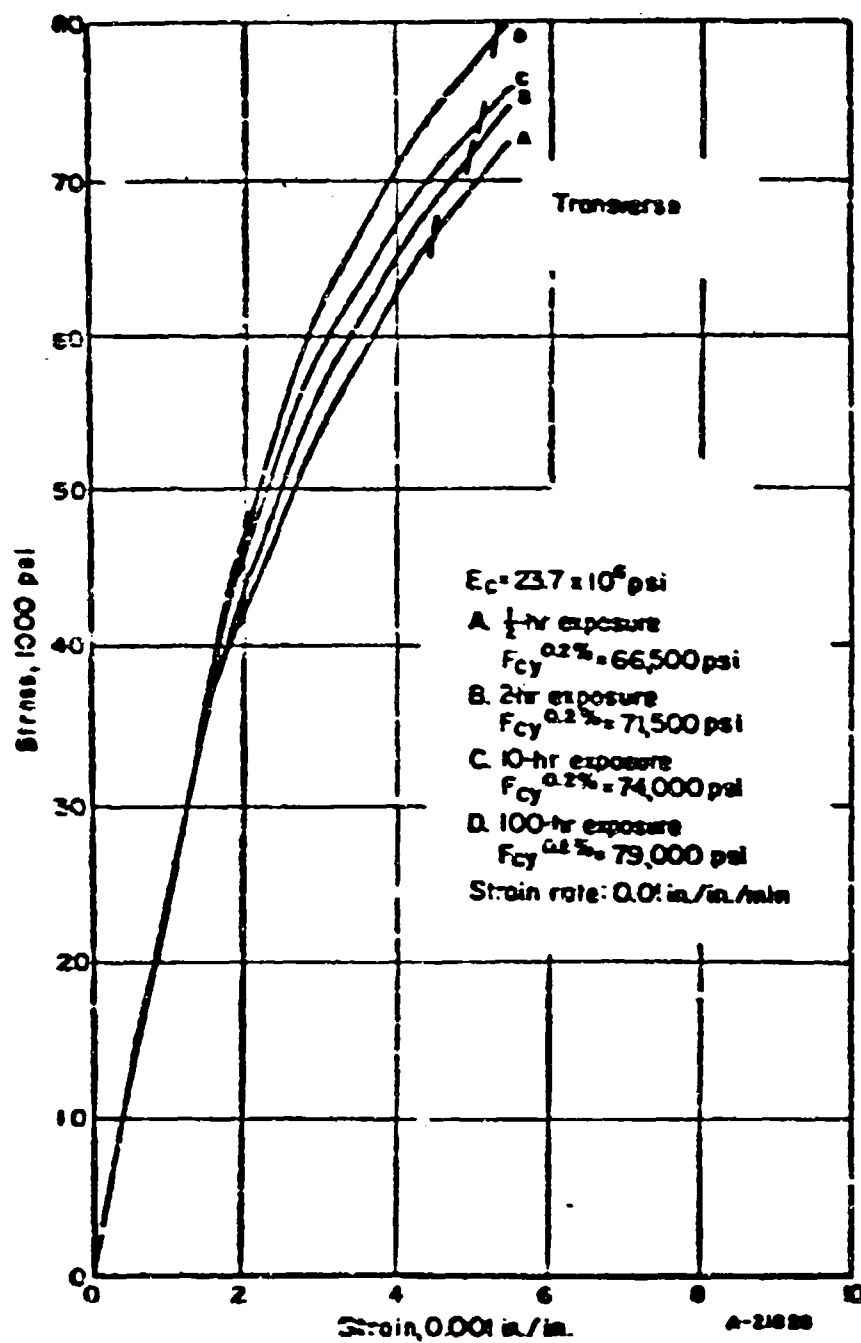


FIGURE 34. COMPRESSIVE STRESS-STRAIN CURVES FOR AISI 301 (HALF HARD) STAINLESS STEEL AT 800 F

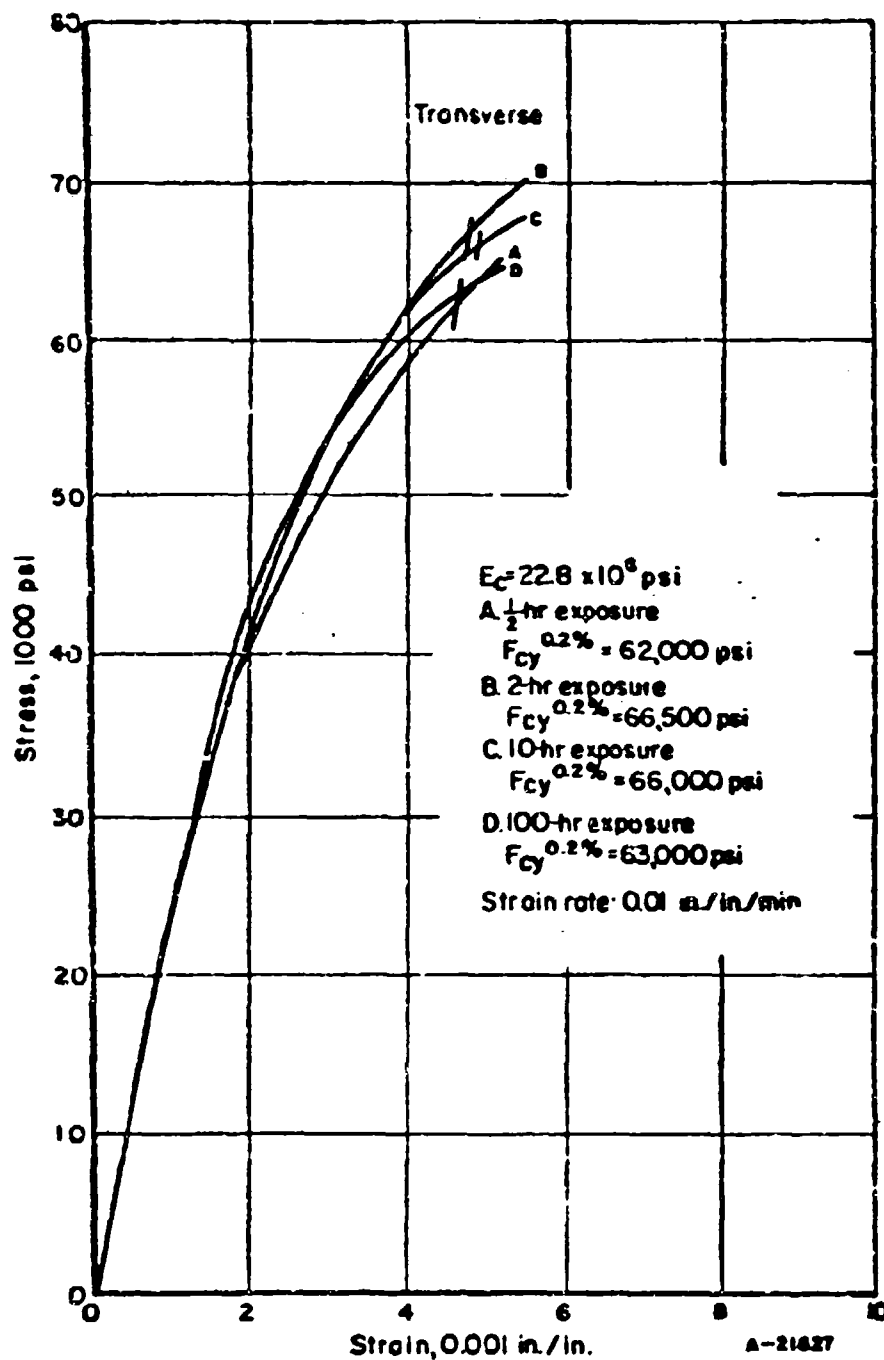


FIGURE 35. COMPRESSIVE STRESS-STRAIN CURVES FOR AISI 301 (HALF HARD) STAINLESS STEEL AT 1000 F

Ref. 57.

WADC TR 55-150

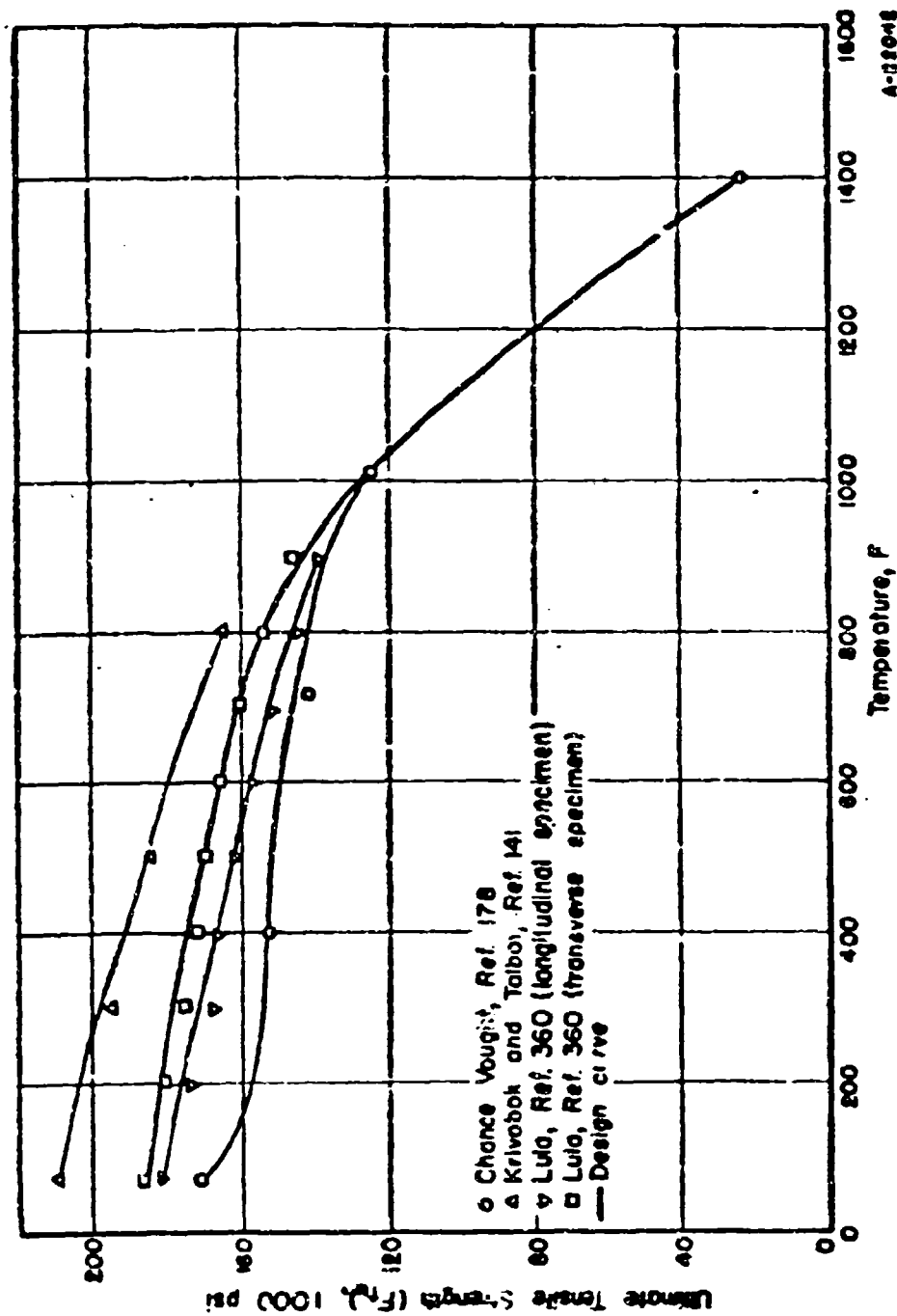


FIGURE 36. TENSILE STRENGTH (F_u) OF AISI 301 (FULL HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE

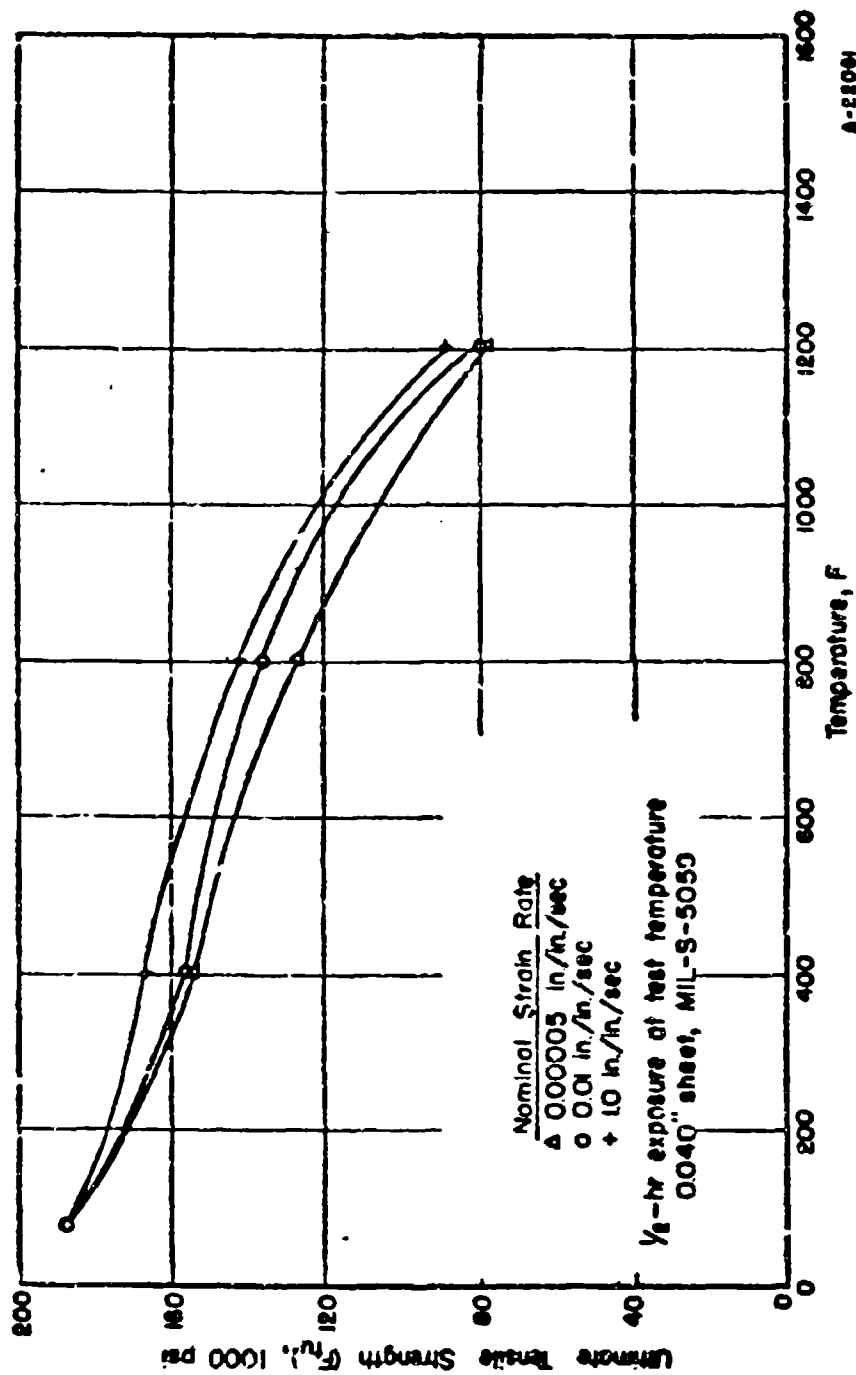


FIGURE 37. EFFECT OF STRAIN RATE ON THE TENSILE STRENGTH (F_{tu}) OF AISI 301 (FULL HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. WADC 55-197, Part 2, p 60.

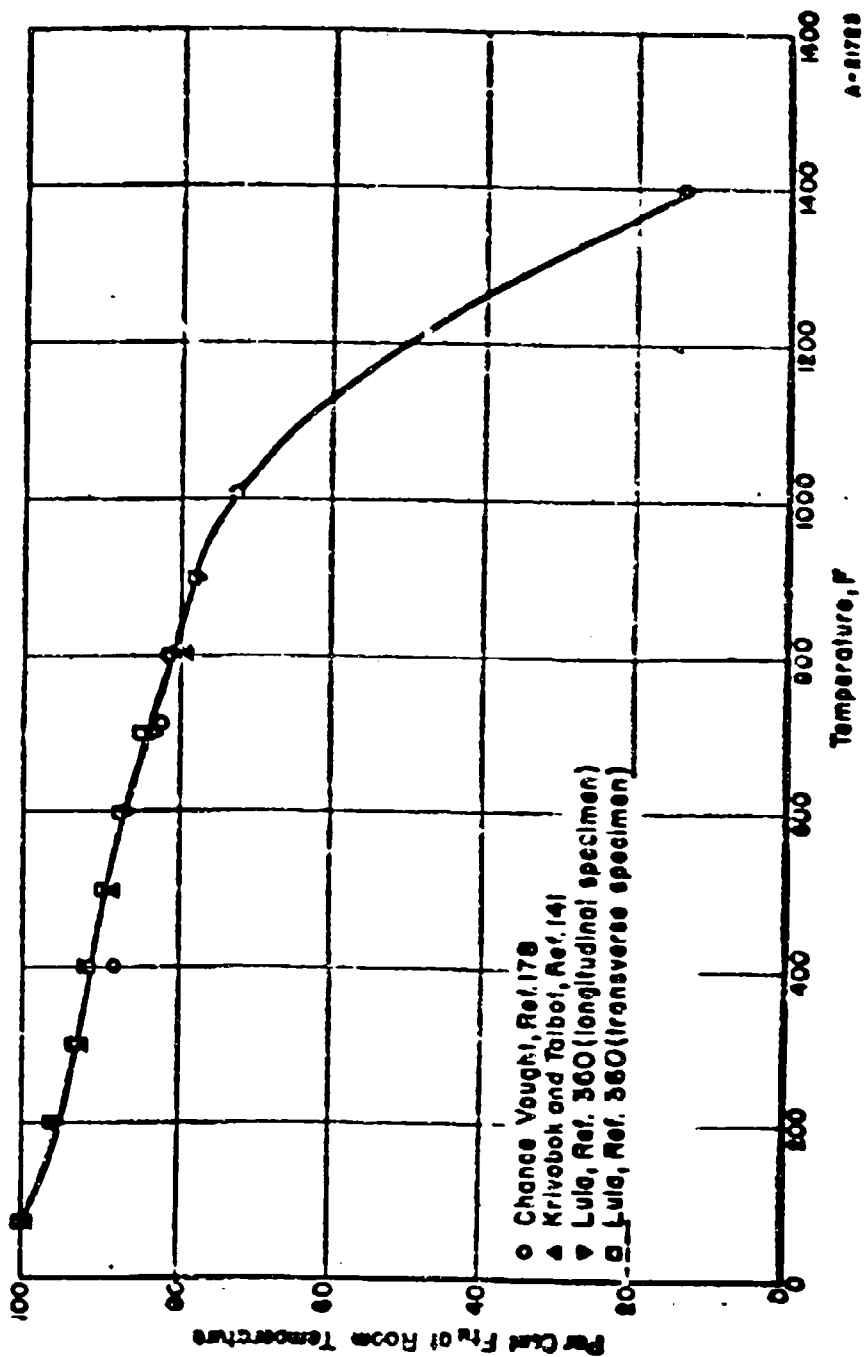


FIGURE 38. TENSILE STRENGTH (F_{10}) EXPRESSED AS A PERCENTAGE OF ROOM-TEMPERATURE TENSILE STRENGTH OF AISI 301 (FULL HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE

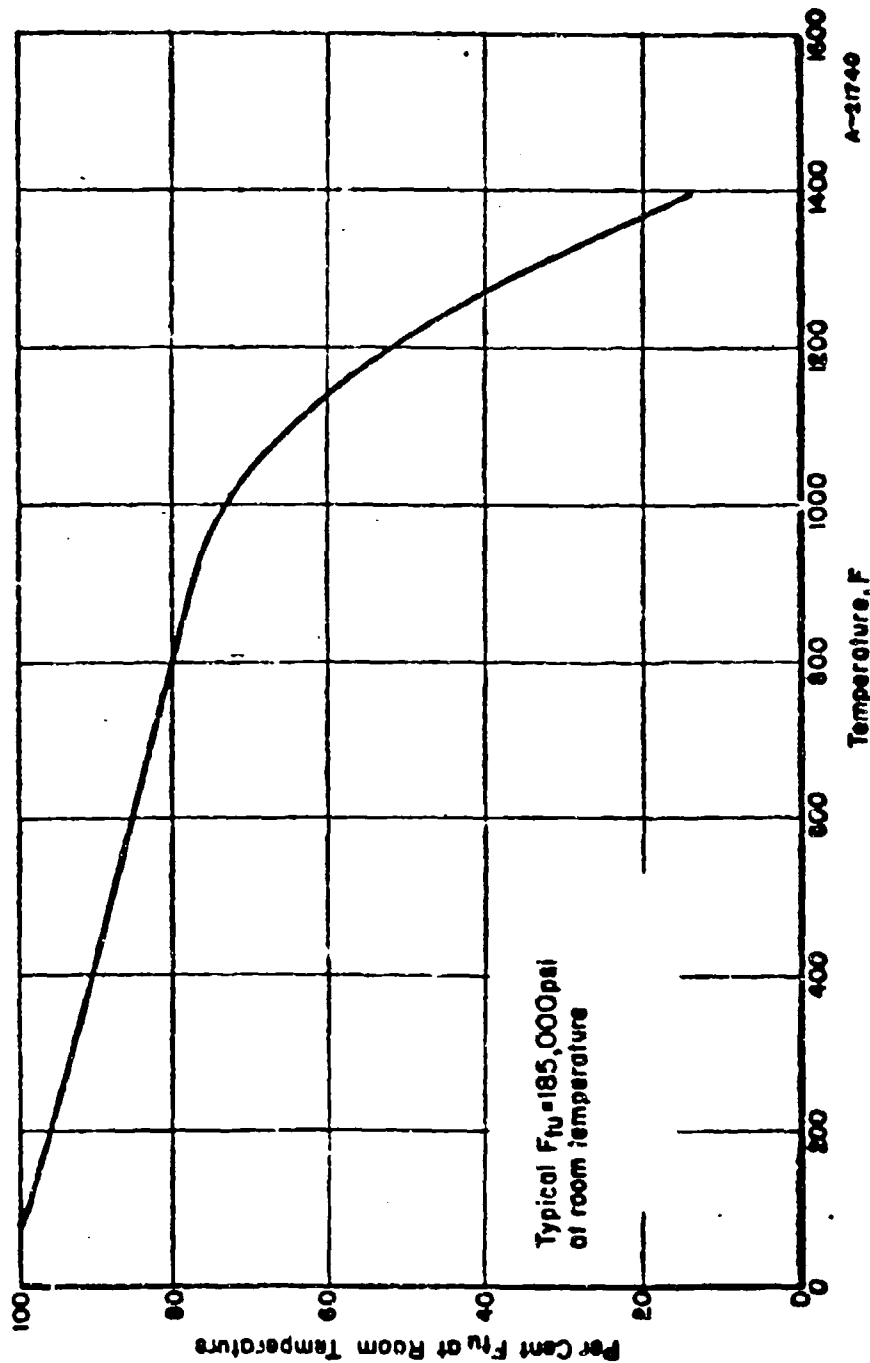


FIGURE 39. DESIGN CURVE FOR TENSILE STRENGTH (F_u) OF AISI 301 (FULL HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 141, 178, 360.

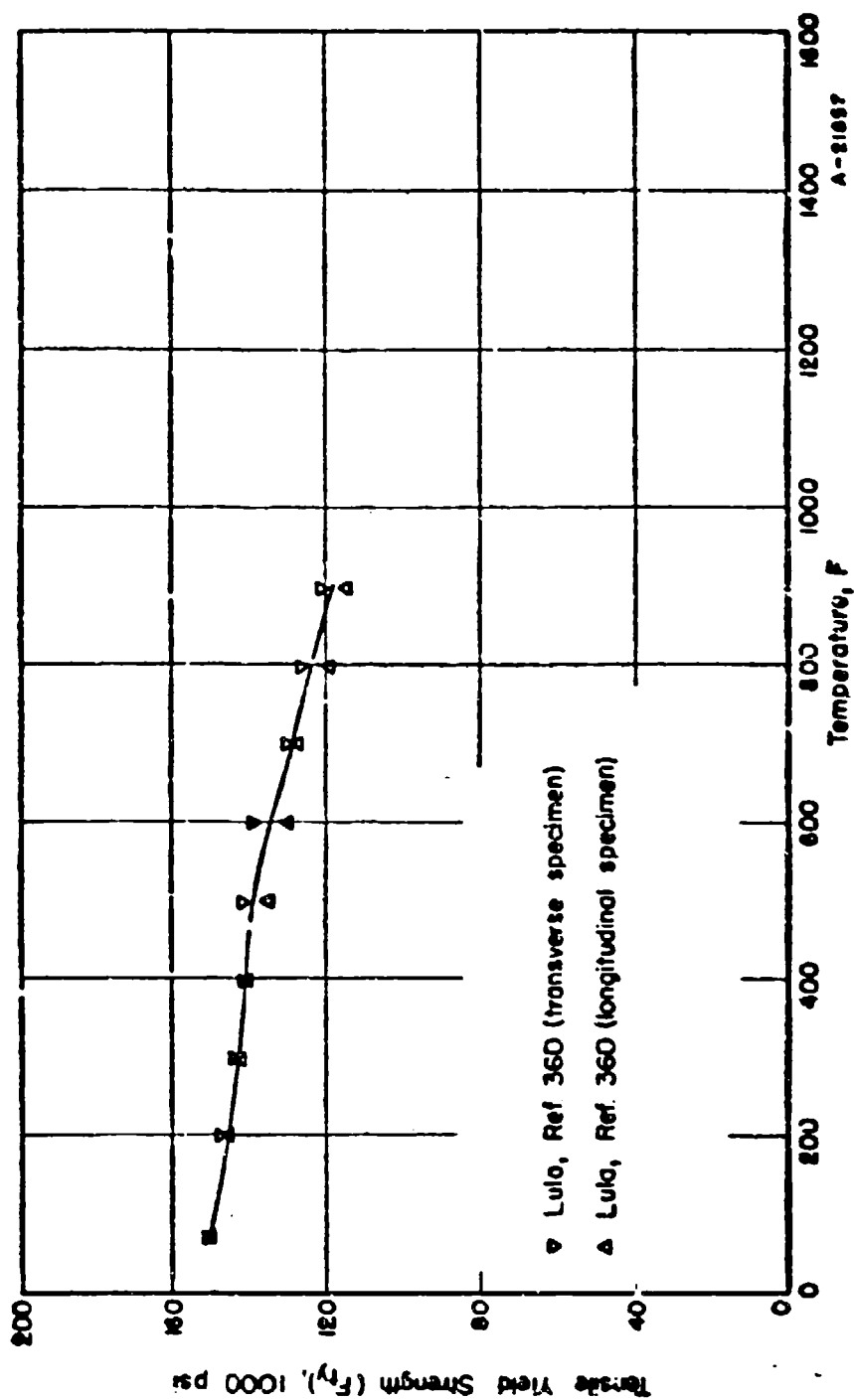


FIGURE 40. TENSILE YIELD STRENGTH (F_y) OF AISI 301 (FULL HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE

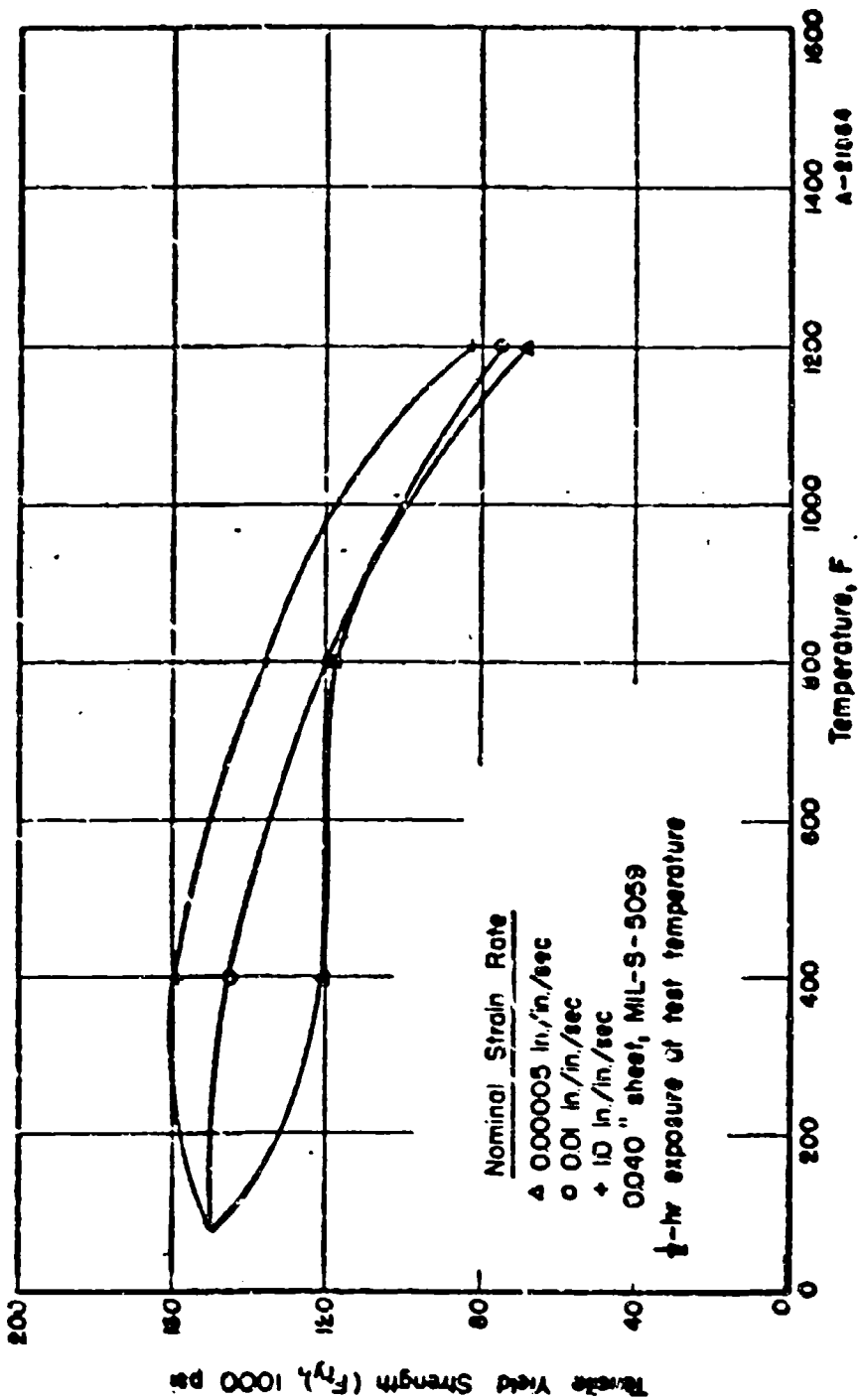


FIGURE 41. EFFECT OF STRAIN RATE ON THE TENSILE YIELD STRENGTH (F_y) OF AISI 301 (FULL HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE

WADC 55-199, Part 2, p 60.

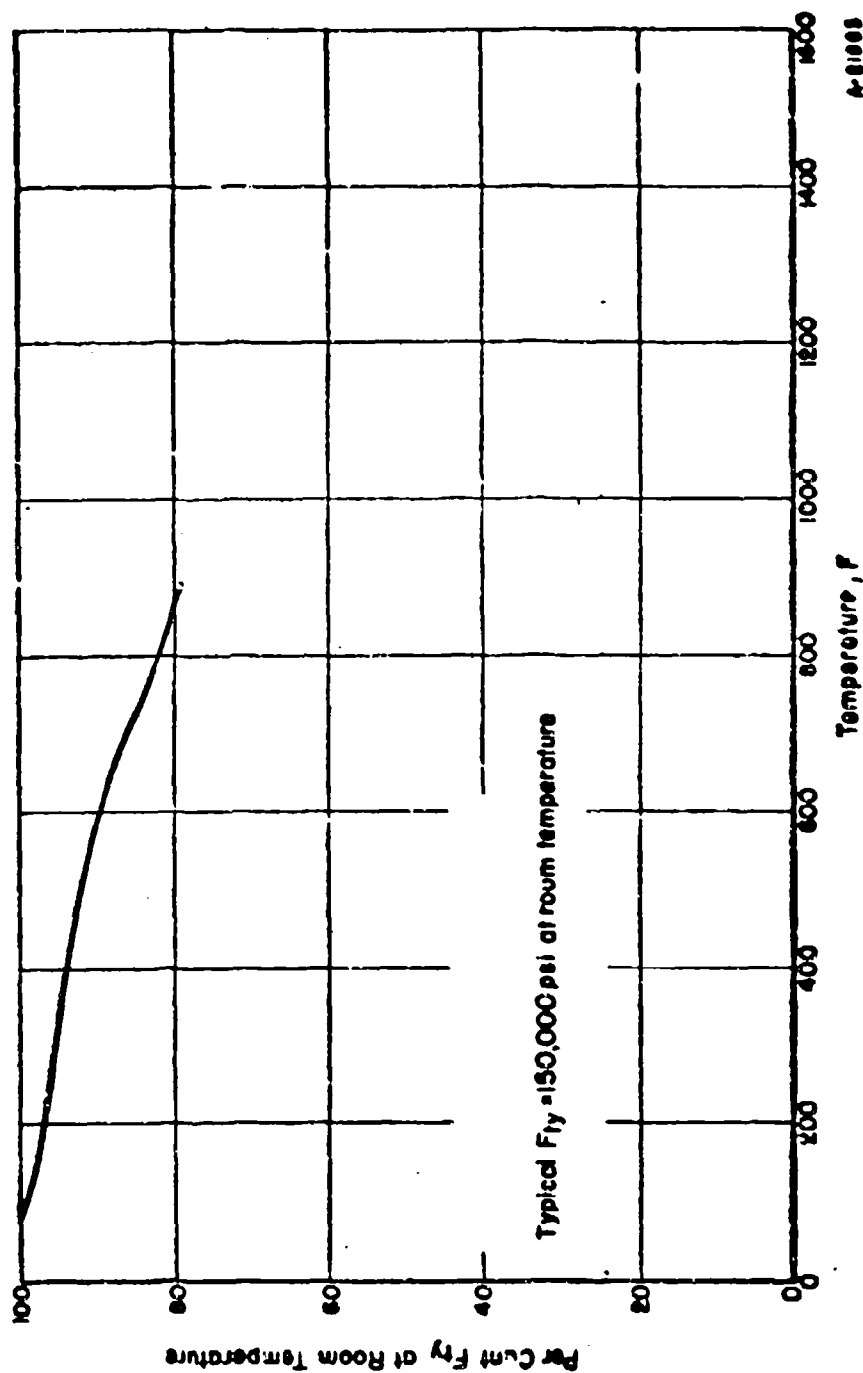


FIGURE 41. DESIGN CURVE FOR TENSILE YIELD STRENGTH (F_{ty}) OF AISI 301 (FULL HARD) STAINLESS STEEL AT ELEVATED TEMPERATURE
Ref. 360.

422M STAINLESS STEEL

The AISI 400 series stainless steels, as a general rule, retain high-strength properties obtained by heat treatment up to above 800 F before embrittlement occurs. A modification of the AISI 420 type resulted in the ferritic 422 grade, which has proven suitable for service around 1000 F. A further improvement resulted in a modified 422, which is similar in characteristics to 422 but possesses appreciably better elevated-temperature strength. The nominal chemical composition of 422M is given in Table 3.

TABLE 3. NOMINAL CHEMICAL
COMPOSITION OF
422M STAINLESS
STEEL

Element	Weight Per Cent
Carbon	0.28
Manganese	0.84
Silicon	0.24
Nickel	0.20
Chromium	11.80
Vanadium	0.49
Tungsten	1.76
Molybdenum	2.24
Iron	Balance

Alloy 422M is referred to as a ferritic grade although it is heat treatable. A typical heat treatment (such as austenitizing at 2000 F, oil quenching, and tempering at 1200 F for 2 hours) results in a microstructure of tempered martensite plus about 10 per cent ferrite. The hardness of the steel after this heat treatment is about Rockwell C 38. Typical short-time, elevated-temperature properties of 422M are shown in the following curves:

Tensile properties, Figures 43 through 46

Stress-strain curves, Figures 47 through 57

For 422M, data are completely lacking for compressive, bearing, and shear strengths, and modulus of elasticity and stress-strain curves at elevated temperatures.

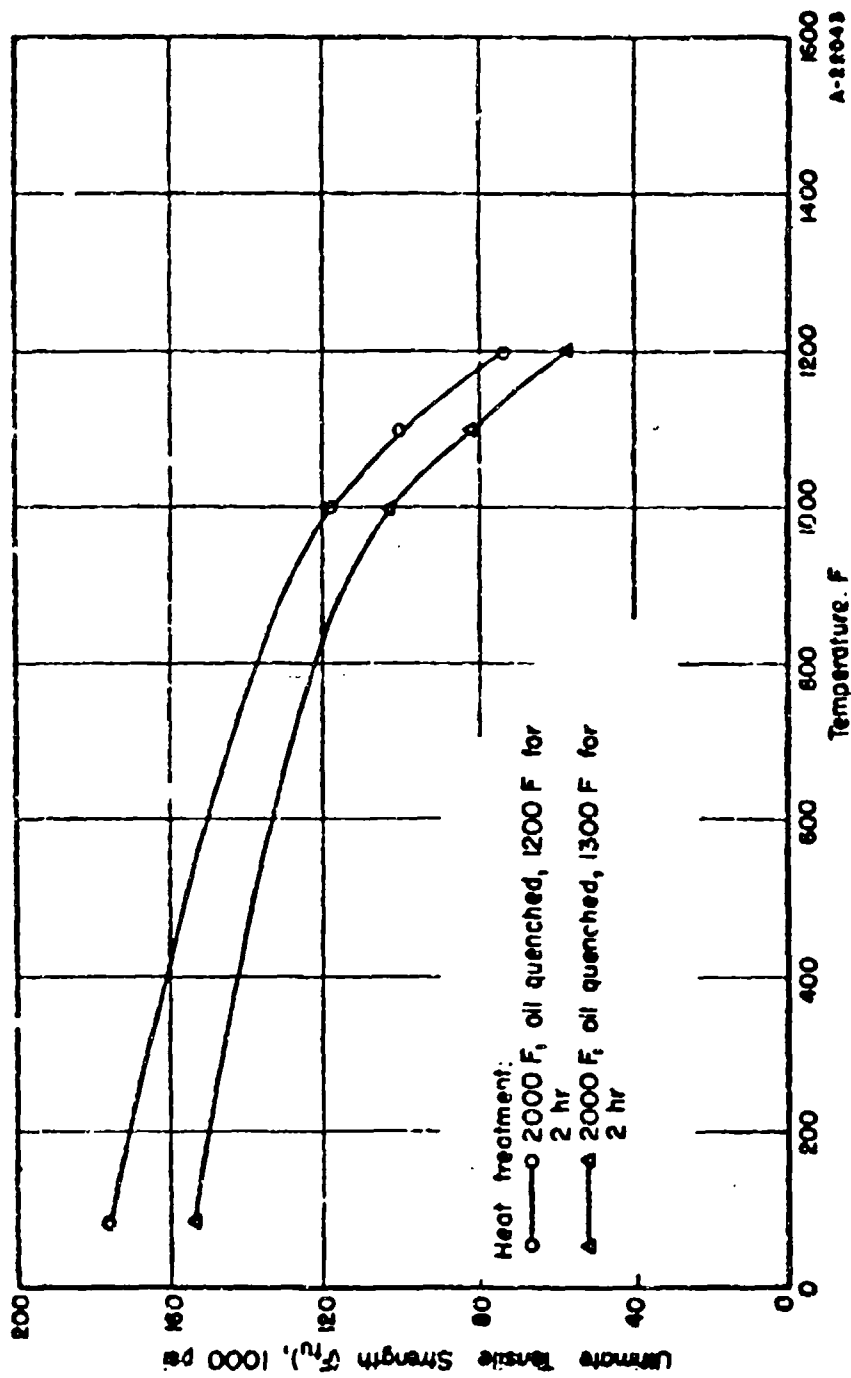


FIGURE 43. TENSILE STRENGTH (F_{tu}) OF 422M STAINLESS STEEL AT ELEVATED TEMPERATURE

A-25043

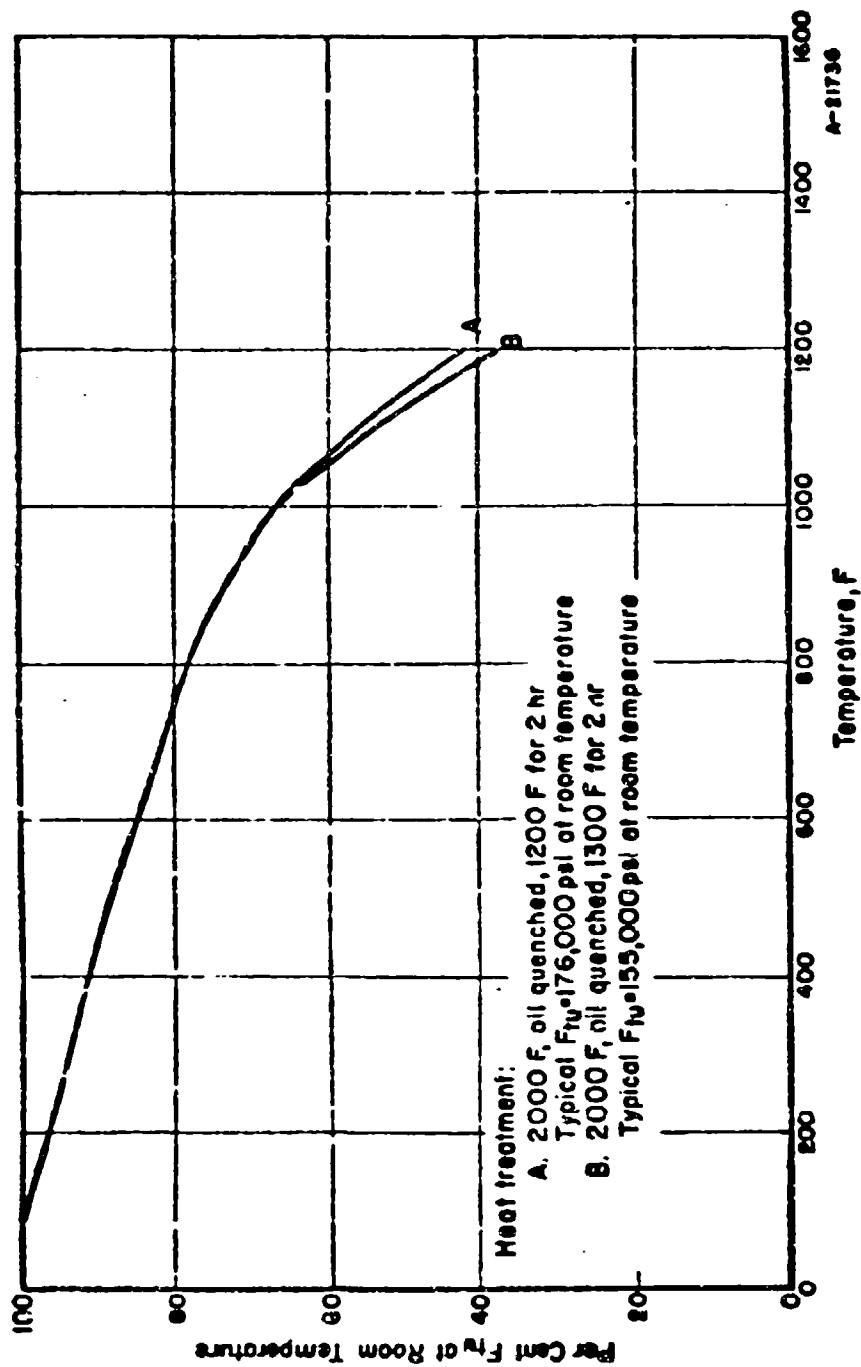


FIGURE 44. DESIGN CURVE FOR TENSILE STRENGTH (F_{tu}) OF 422M STAINLESS STEEL AT ELEVATED TEMPERATURE

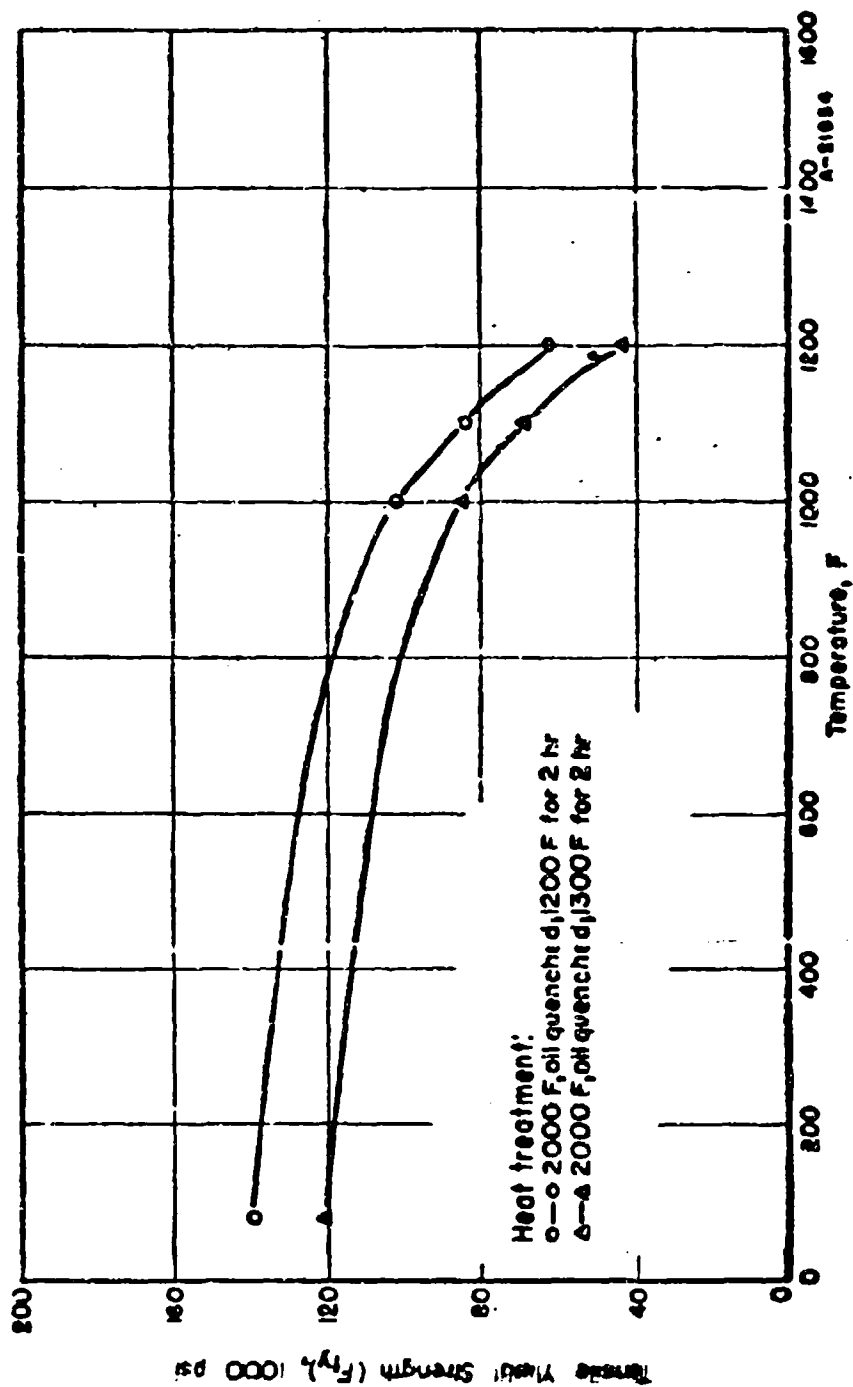


FIGURE 45. TENSILE YIELD STRENGTH (F_y) OF 422M STAINLESS STEEL AT ELEVATED TEMPERATURE

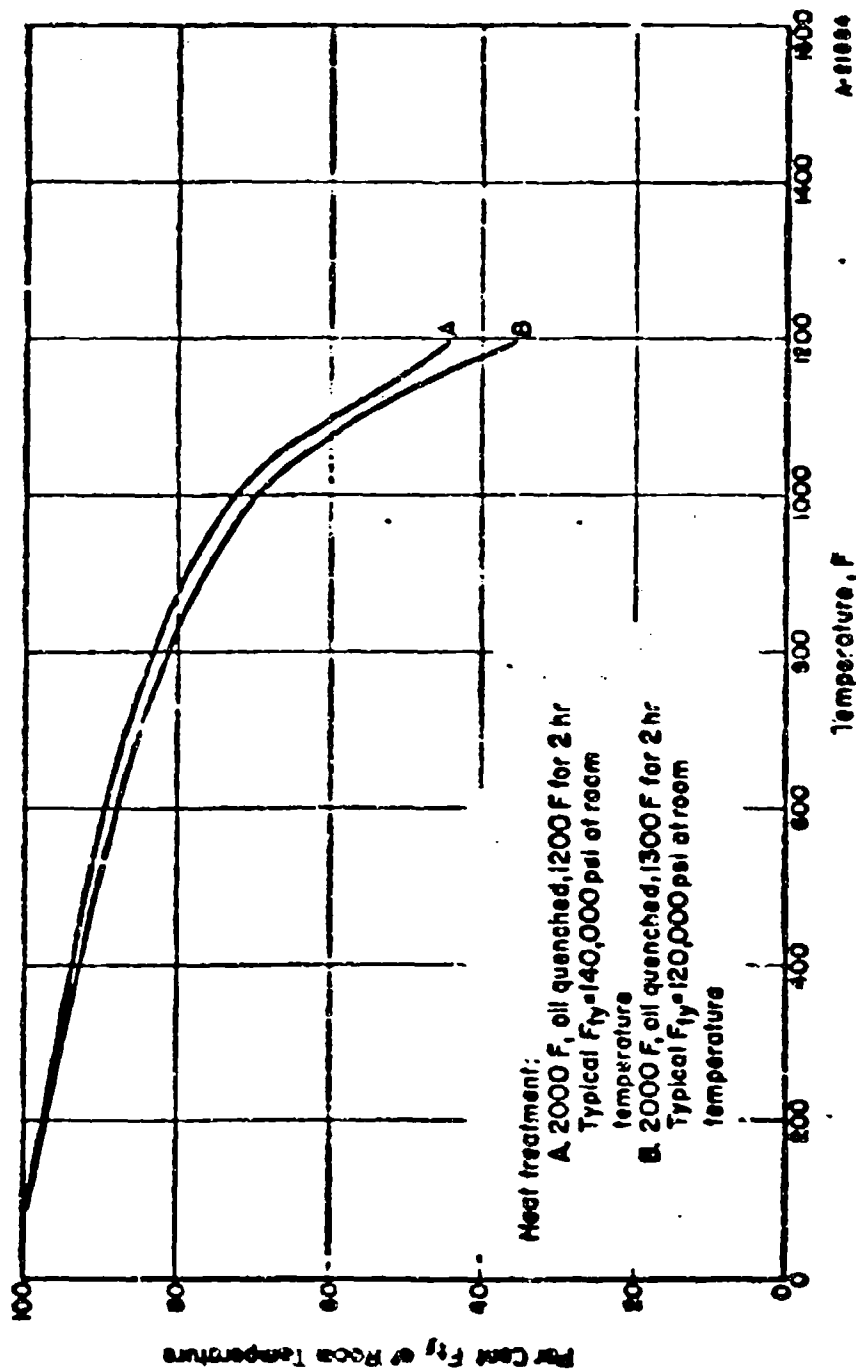


FIGURE 46. DESIGN CURVE FOR TENSILE YIELD STRENGTH (F_{ty}) OF 422M STAINLESS STEEL AT ELEVATED TEMPERATURE

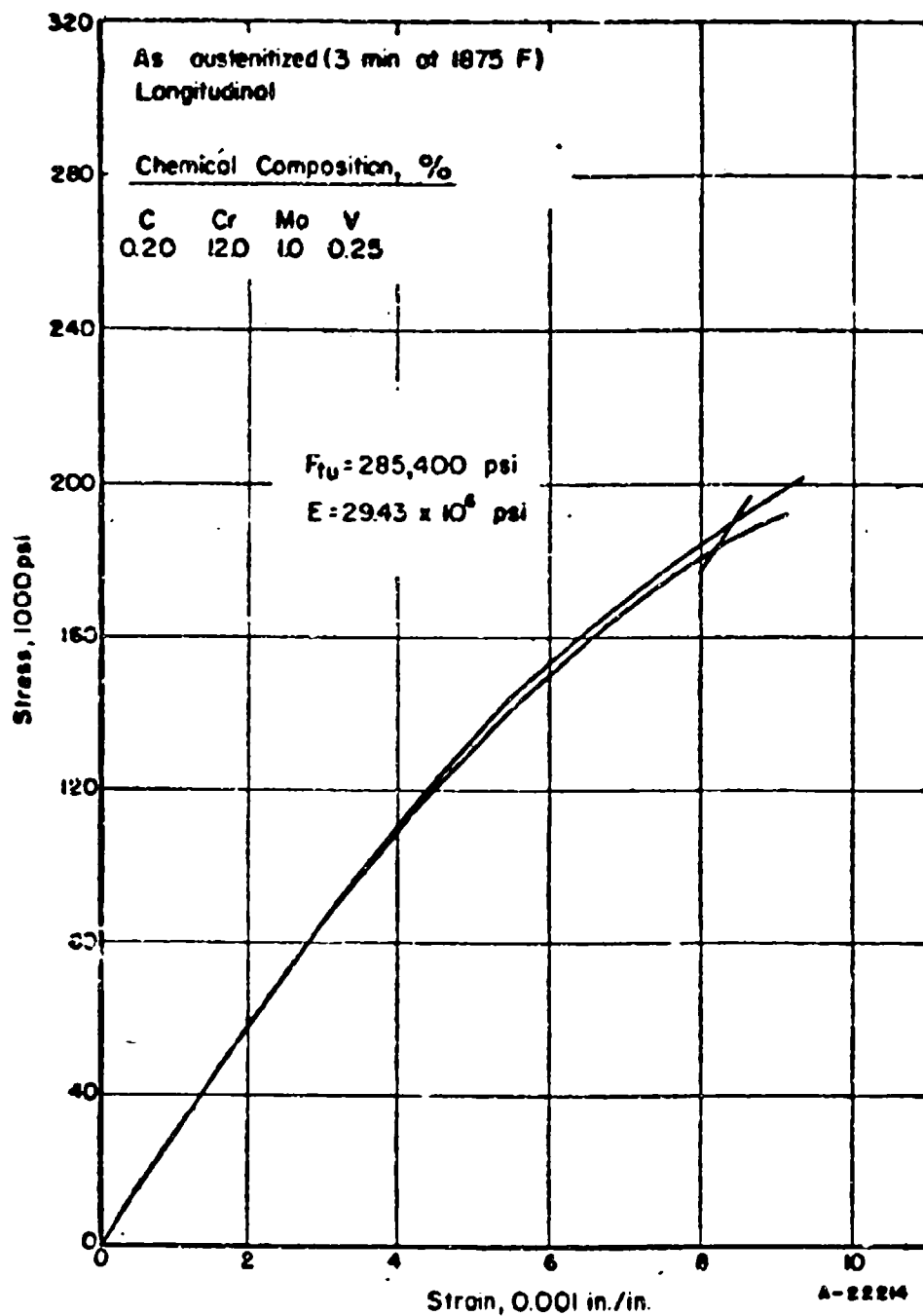


FIGURE 47. TENSILE STRESS-STRAIN CURVES FOR 422M STAINLESS STEEL AT ROOM TEMPERATURE

Ref. 345.

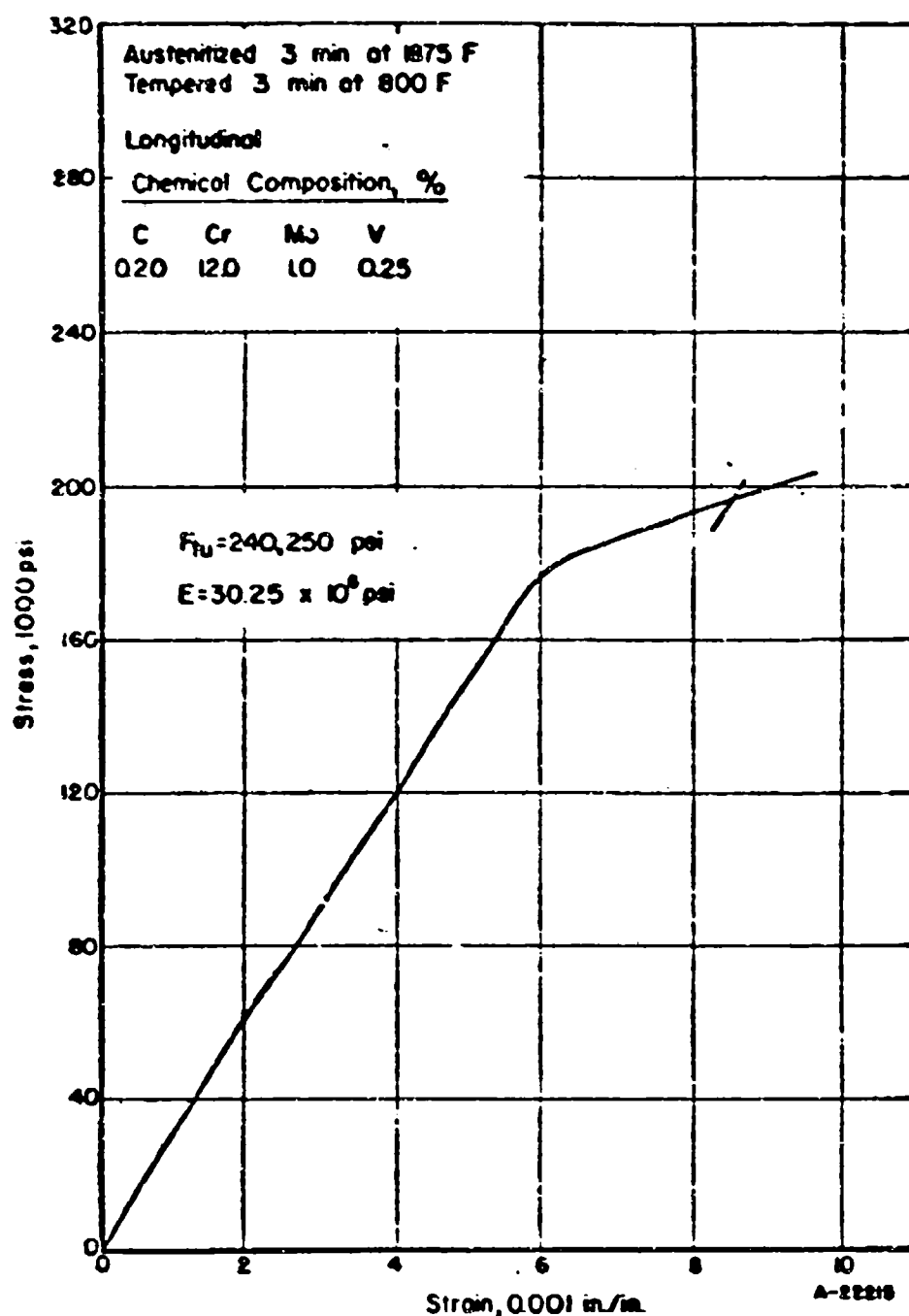


FIGURE 46. TENSILE STRESS-STRAIN CURVE FOR 422M STAINLESS STEEL AT ROOM TEMPERATURE

Ref. 349.

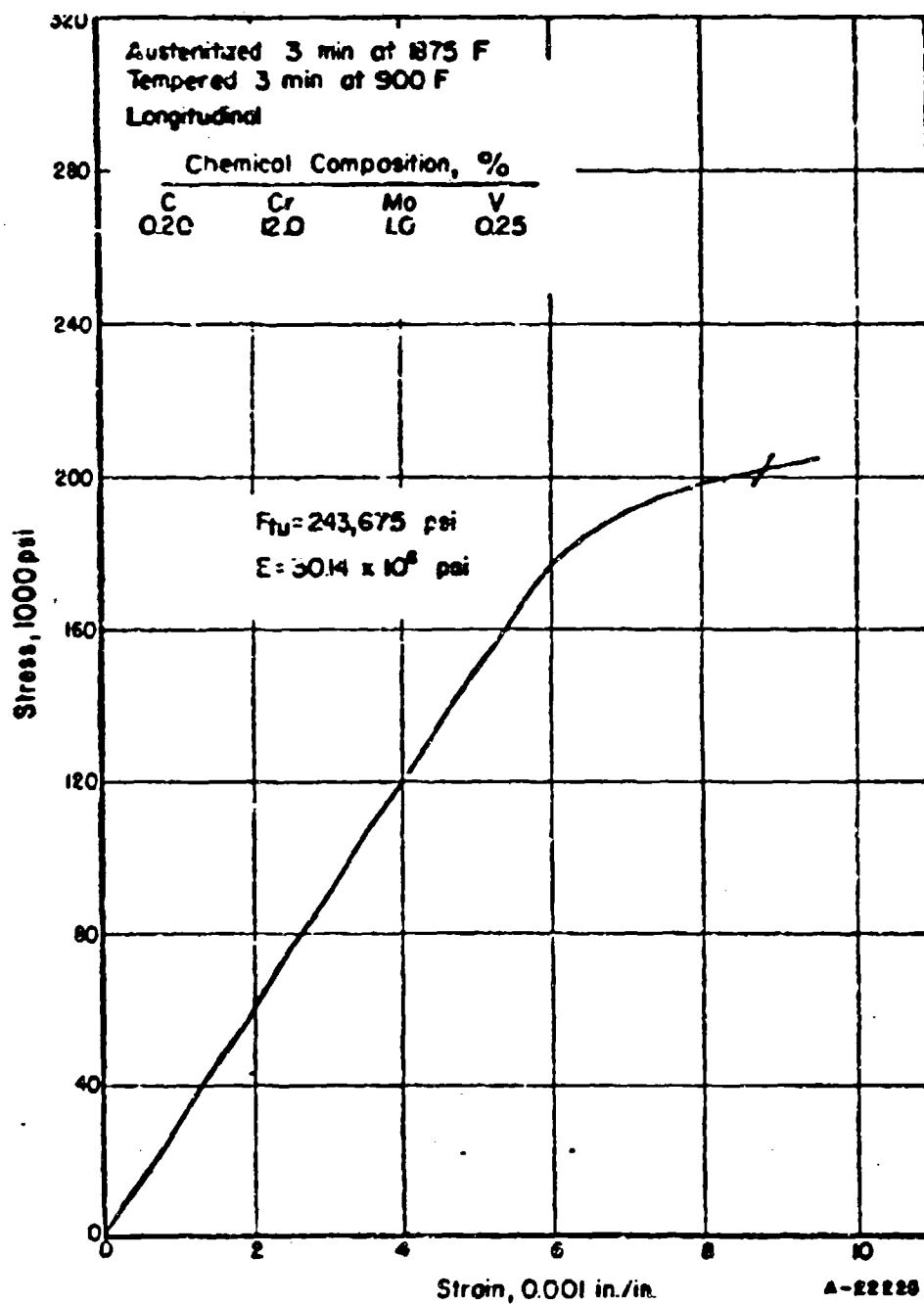


FIGURE 49. TENSILE STRESS-STRAIN CURVE FOR 422M
STAINLESS STEEL AT ROOM TEMPERATURE

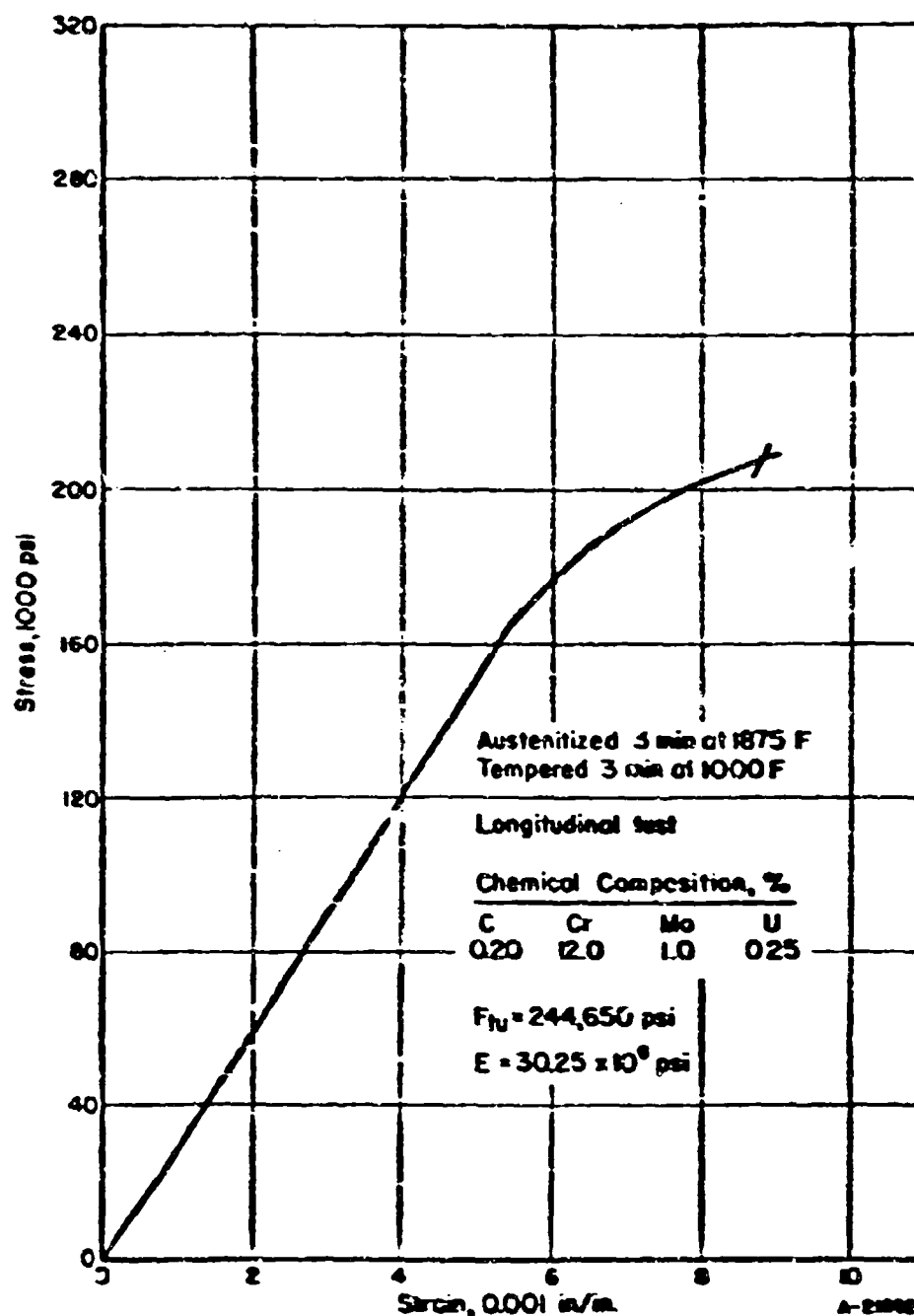


FIGURE 50. TENSILE STRESS-STRAIN CURVE FOR 422M STAINLESS STEEL AT ROOM TEMPERATURE

Ref. 208.

WADC TR 55-150 P. 1

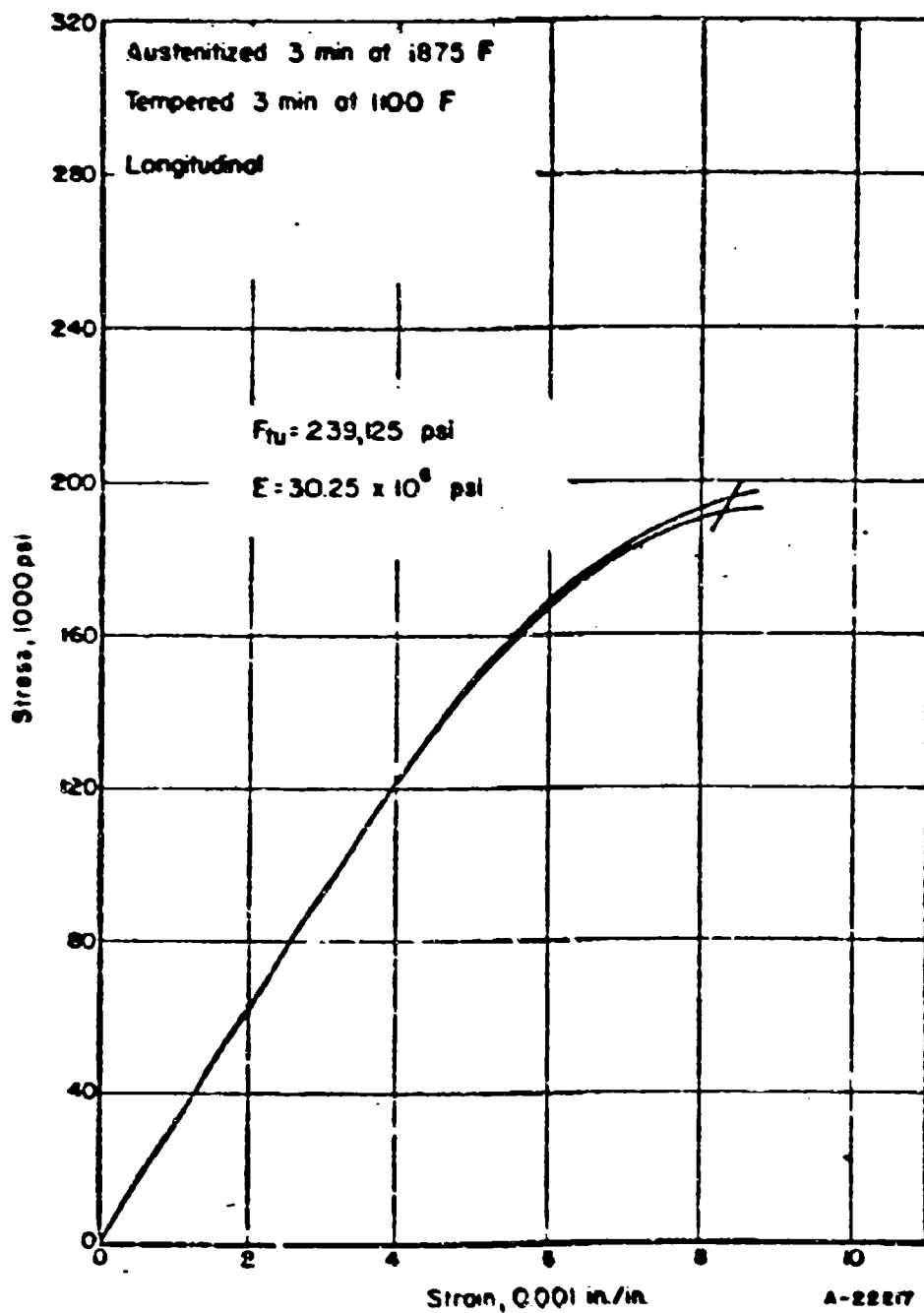


FIGURE 51. TENSILE STRESS-STRAIN CURVES FOR 422M STAINLESS STEEL AT ROOM TEMPERATURE

Ref. 349.

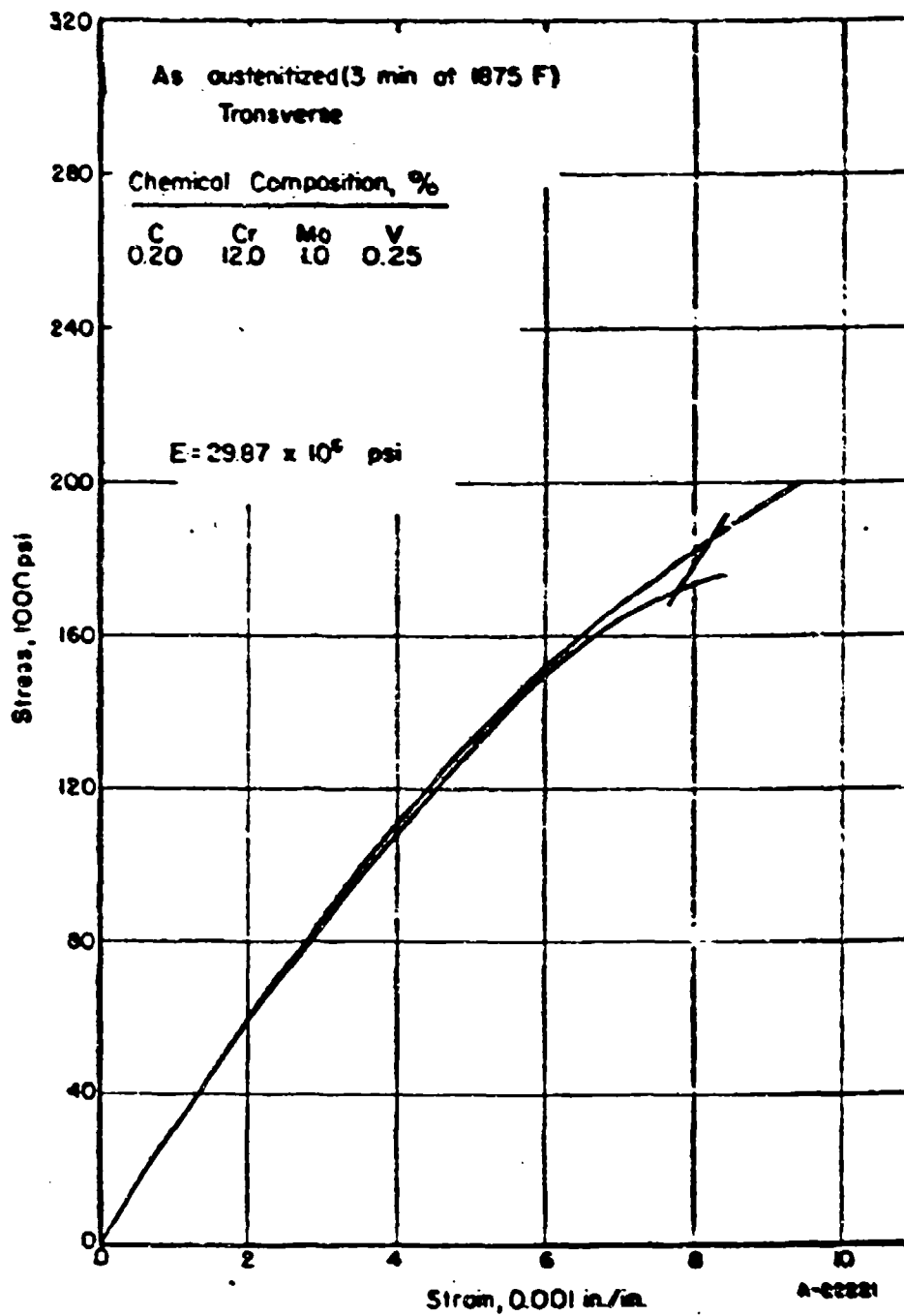


FIGURE 52. TENSILE STRESS-STRAIN CURVES FOR 422M STAINLESS STEEL AT ROOM TEMPERATURE

Ref. 349.

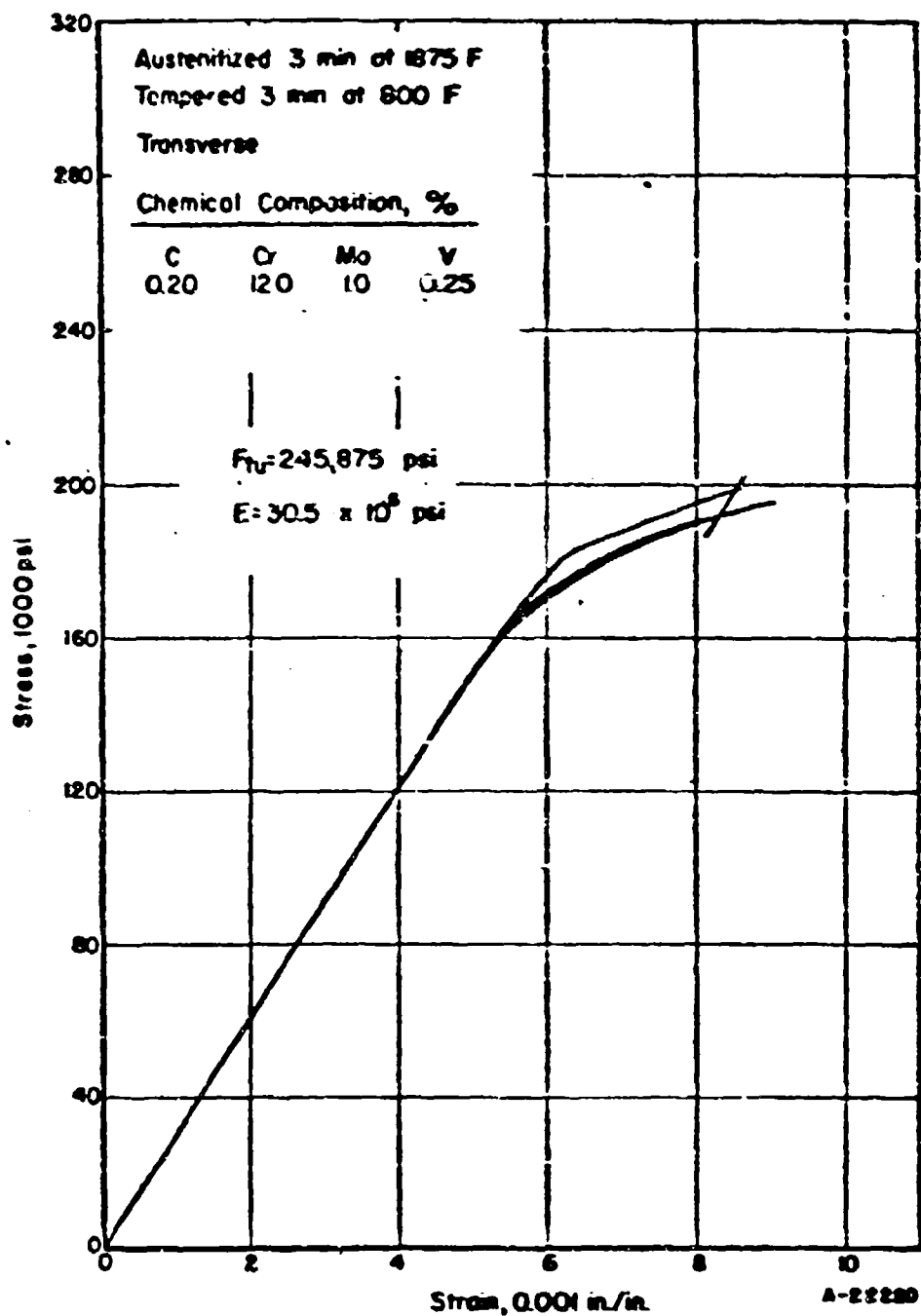


FIGURE 53. TENSILE STRESS-STRAIN CURVES FOR 422M STAINLESS STEEL AT ROOM TEMPERATURE

Ref. 349.

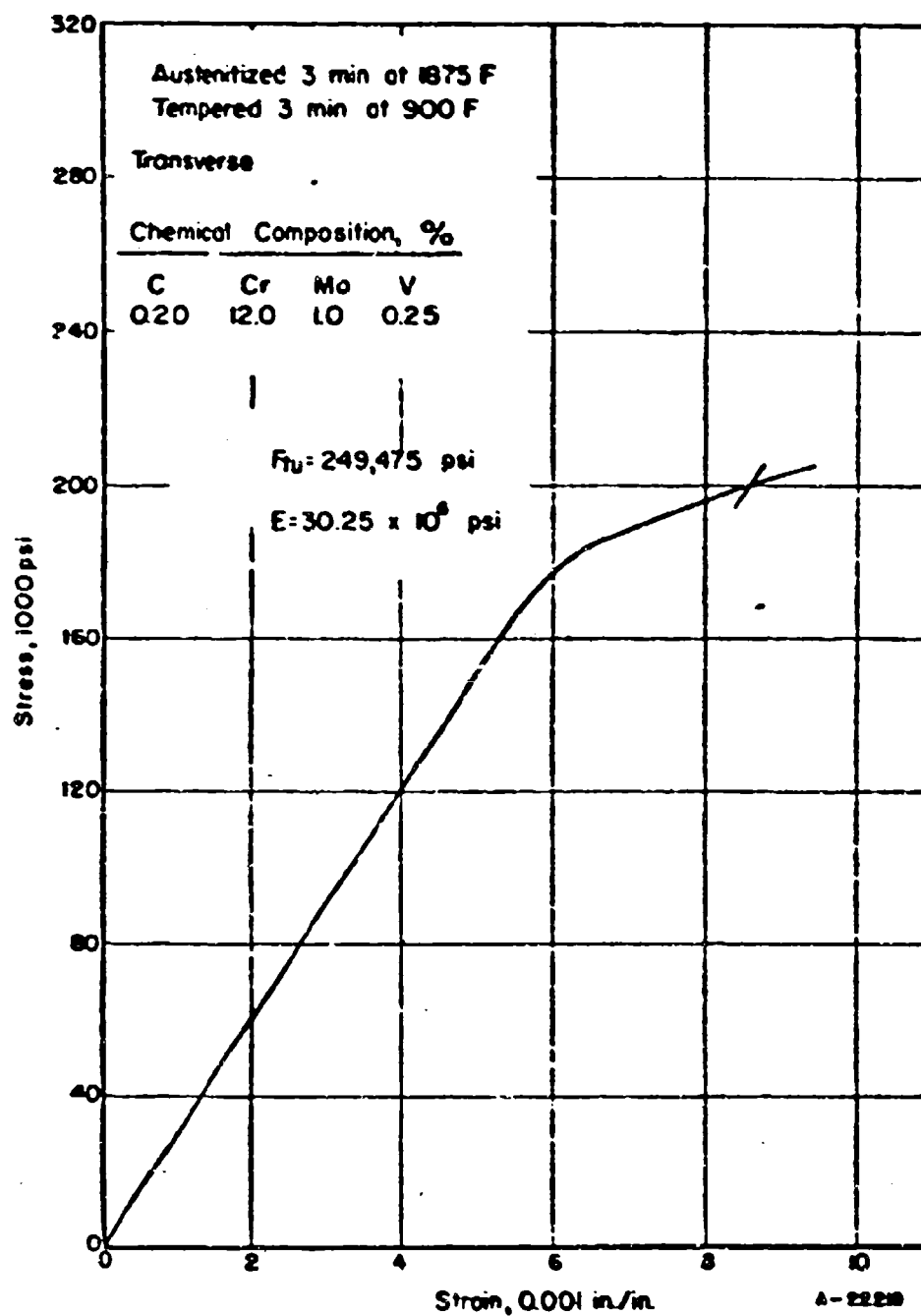


FIGURE 54. TENSILE STRESS-STRAIN CURVE FOR 422M STAINLESS STEEL AT ROOM TEMPERATURE

Ref. 349.

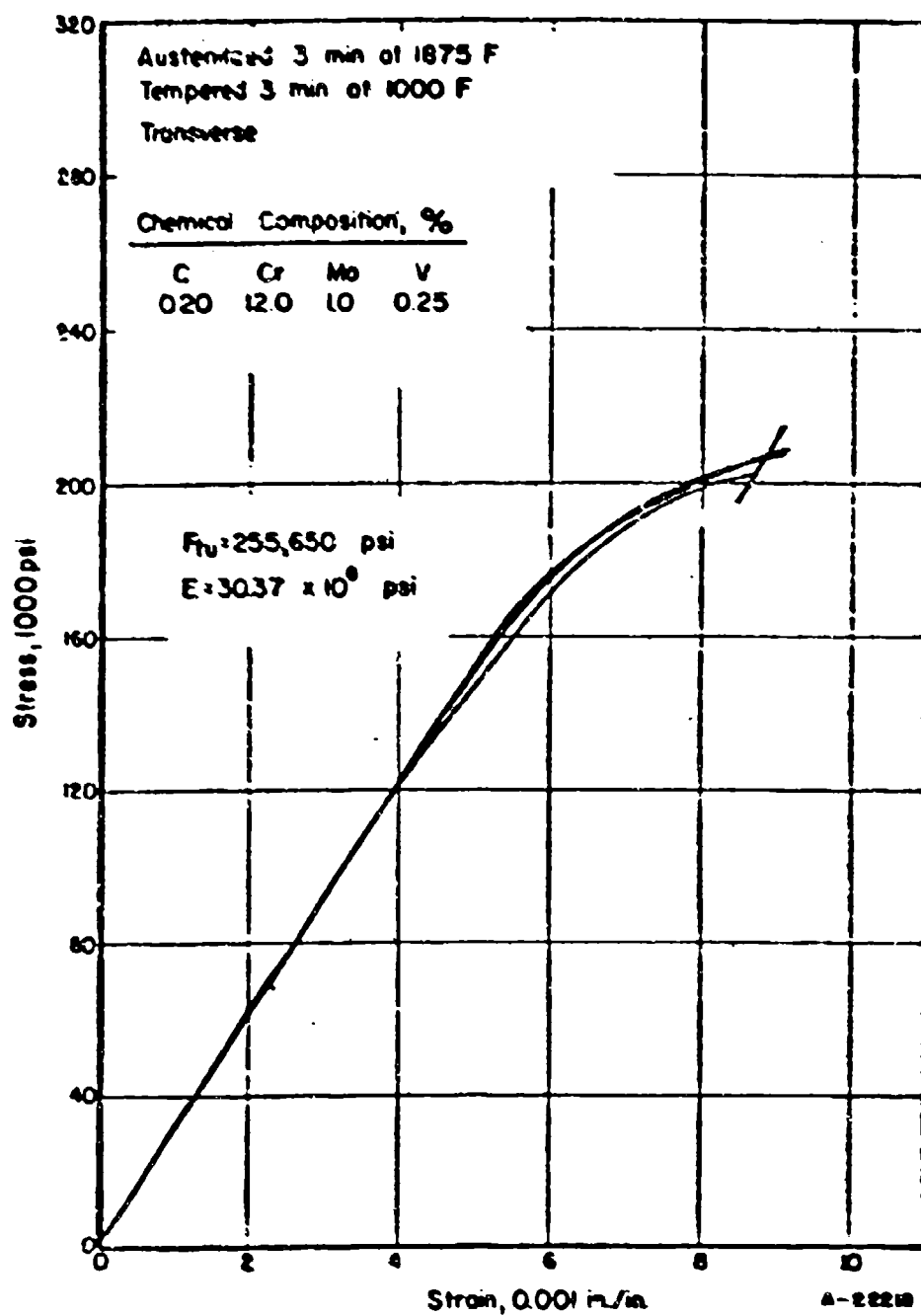


FIGURE 58. TENSILE STRESS-STRAIN CURVES FOR 422M STAINLESS STEEL AT ROOM TEMPERATURE

Ref. 349.

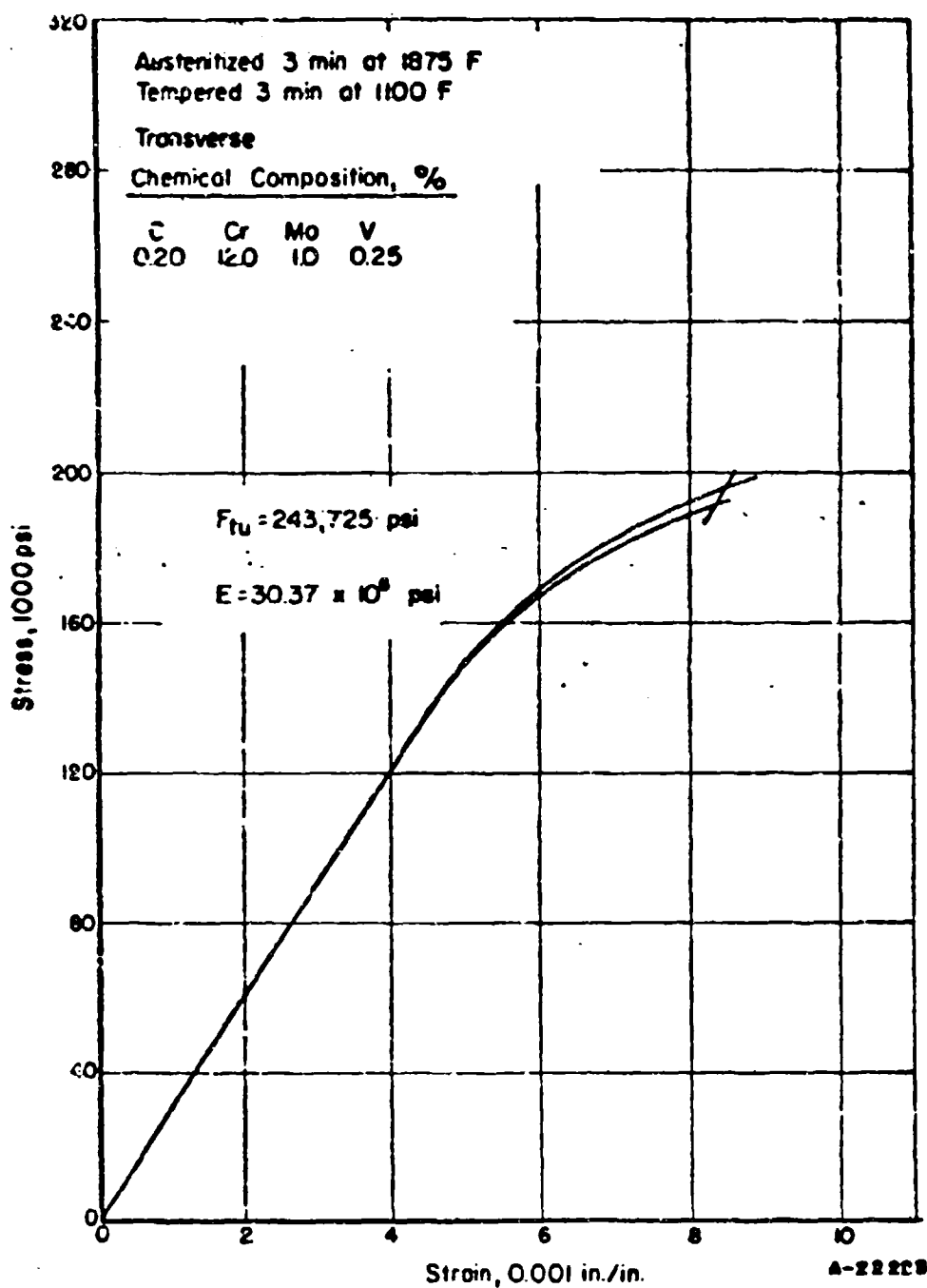


FIGURE 56. TENSILE STRESS-STRAIN CURVES FOR 422M STAINLESS STEEL AT ROOM TEMPERATURE

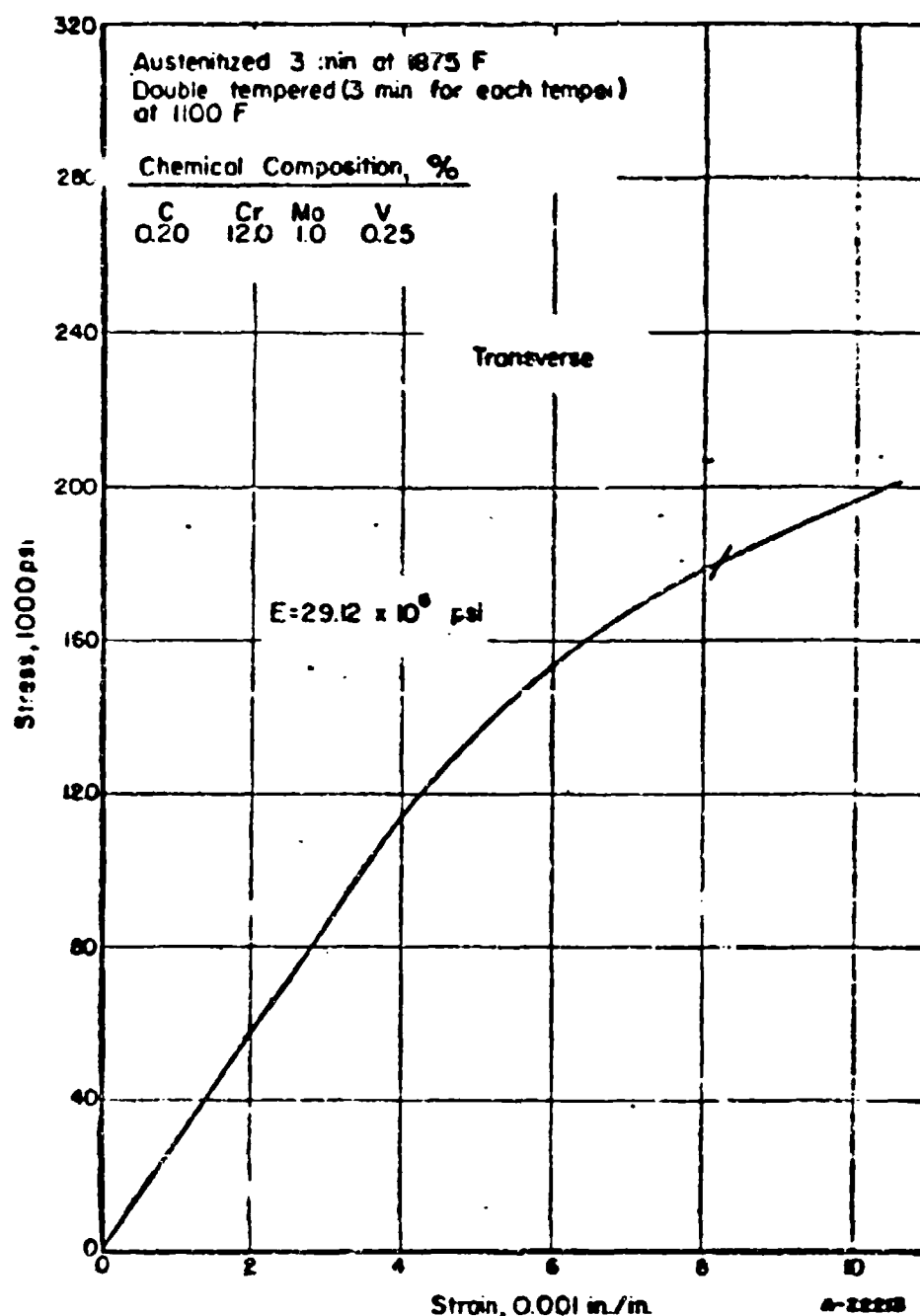


FIGURE 57. TENSILE STRESS-STRAIN CURVE FOR 422M
STAINLESS STEEL AT ROOM TEMPERATURE

Ref. 349.

17-7PH STAINLESS STEEL
(AMS-5528)

17-7PH is a precipitation-hardenable stainless steel that has good strength properties up to 700 F. The composition is balanced so that, as annealed, the alloy is austenitic. Hardening is accomplished by a double heat treatment. The first heat treatment is at 1400 F to precipitate chromium carbides and thereby render the alloy unstable; then, on cooling to below 250 F the austenite transforms to martensite (with transformation essentially complete at 60 F). The second heat treatment is at 950 to 1050 F to promote precipitation of what are thought to be aluminum compounds in the martensitic matrix(358)*. The nominal chemical composition for 17-7PH is shown in Table 4, and minimum tensile properties are given in Table 5.

TABLE 4. NOMINAL CHEMICAL
COMPOSITION OF
17-7PH STAINLESS
STEEL (AMS-5528)

Element	Weight Per Cent
Carbon, Maximum	0.09
Chromium	17.00
Nickel	7.00
Aluminum	1.20
Iron	Balance

TABLE 5. MINIMUM MECHANICAL PROPERTIES
OF 17-7PH STAINLESS STEEL

Property	Condition (TH-1050) (AMS-5528)	Condition (TH-950) No Specification Available
Ultimate Tensile(F_{tu})	180,000 psi	185,000 psi
Tensile Yield (F_{ty})	150,000 psi	165,000 psi
Elongation(e) in 2 inches	6 per cent	6 per cent

*See bibliography in Appendix II.

Condition TH 1050

Condition TH 1050 is developed in steps from Condition A and then Condition Y. The steel is first solution annealed at $1950\text{ F} \pm 25\text{ F}$ for 3 minutes per each 0.1 inch of thickness. This treatment drives the chromium carbides into solution in the austenite, thus stabilizing the austenite against martensitic transformation and effectively depresses the M_s temperature. This brings the steel to Condition A. The steel is then treated at $1400\text{ F} \pm 25\text{ F}$ for 90 minutes which results in Condition Y. The steel is now conditioned so that sufficient austenite transformation can be obtained at 60 F on cooling. Finally, Condition TH 1050 is attained by precipitation hardening at 1050 F .

Condition TH 950

Condition TH 950 is developed in the same way, except that the final precipitation hardening takes place at 950 F .

The short-time, elevated-temperature properties of 17-7PH are shown in the following curves:

- (1) Tensile properties, Figures 55 through 63 and 66 through 89
- (2) Compressive properties, Figures 64 and 65
- (3) Bearing properties, Figures 66 through 69
- (4) Shear properties, Figures 70 and 71
- (5) Modulus of elasticity, Figures 72, 78, and 83
- (6) Stress-strain curves, Figures 73 through 77, 79 through 83, and 85.

Design properties of 17-7PH (TH 1050) are fairly well established, but only tensile properties are available for 17-7PH (TH 950).

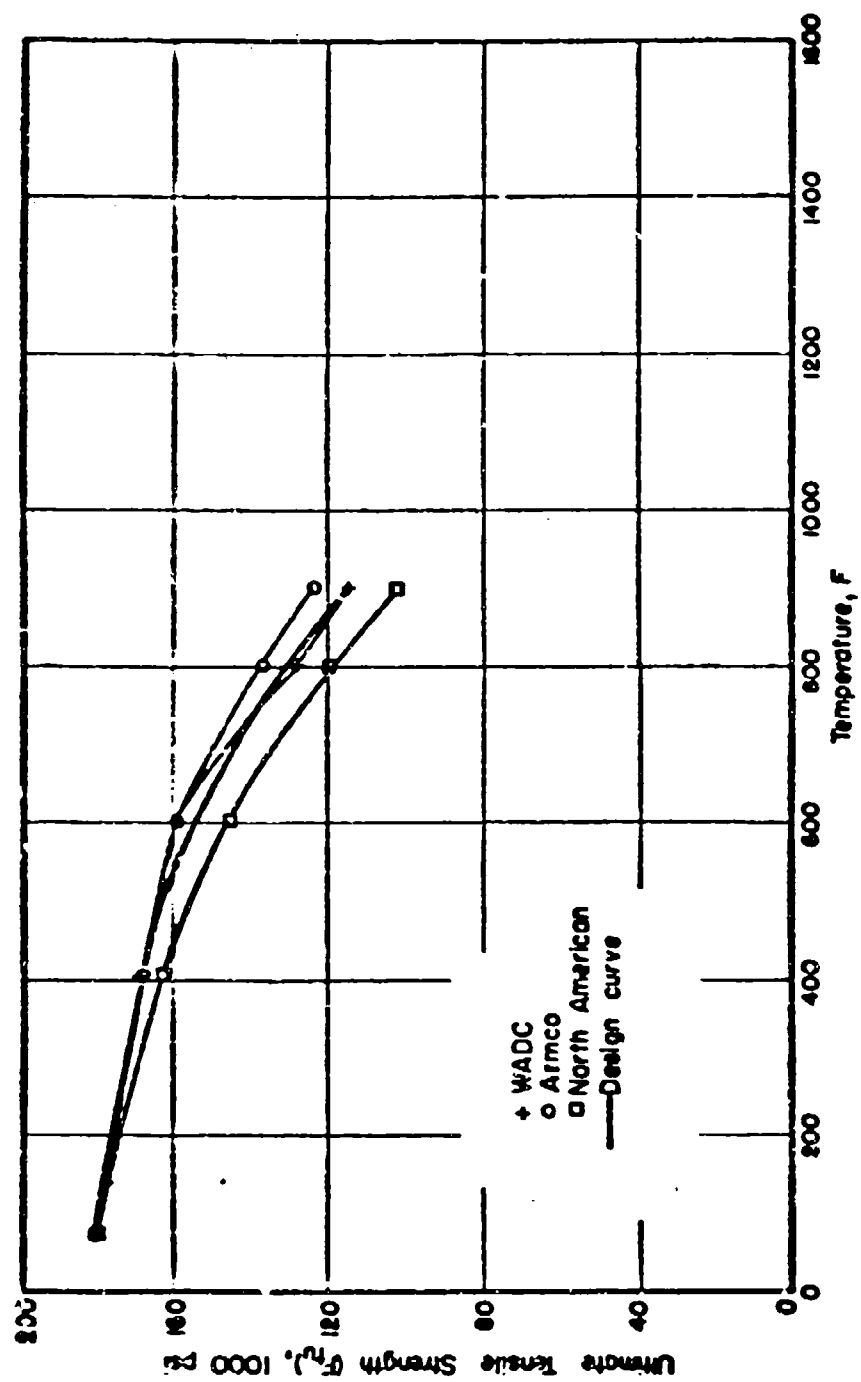


FIGURE 58. TENSILE STRENGTH (F_{tu}) OF 17-7PH (TH 1050) STAINLESS STEEL AT ELEVATED TEMPERATURE

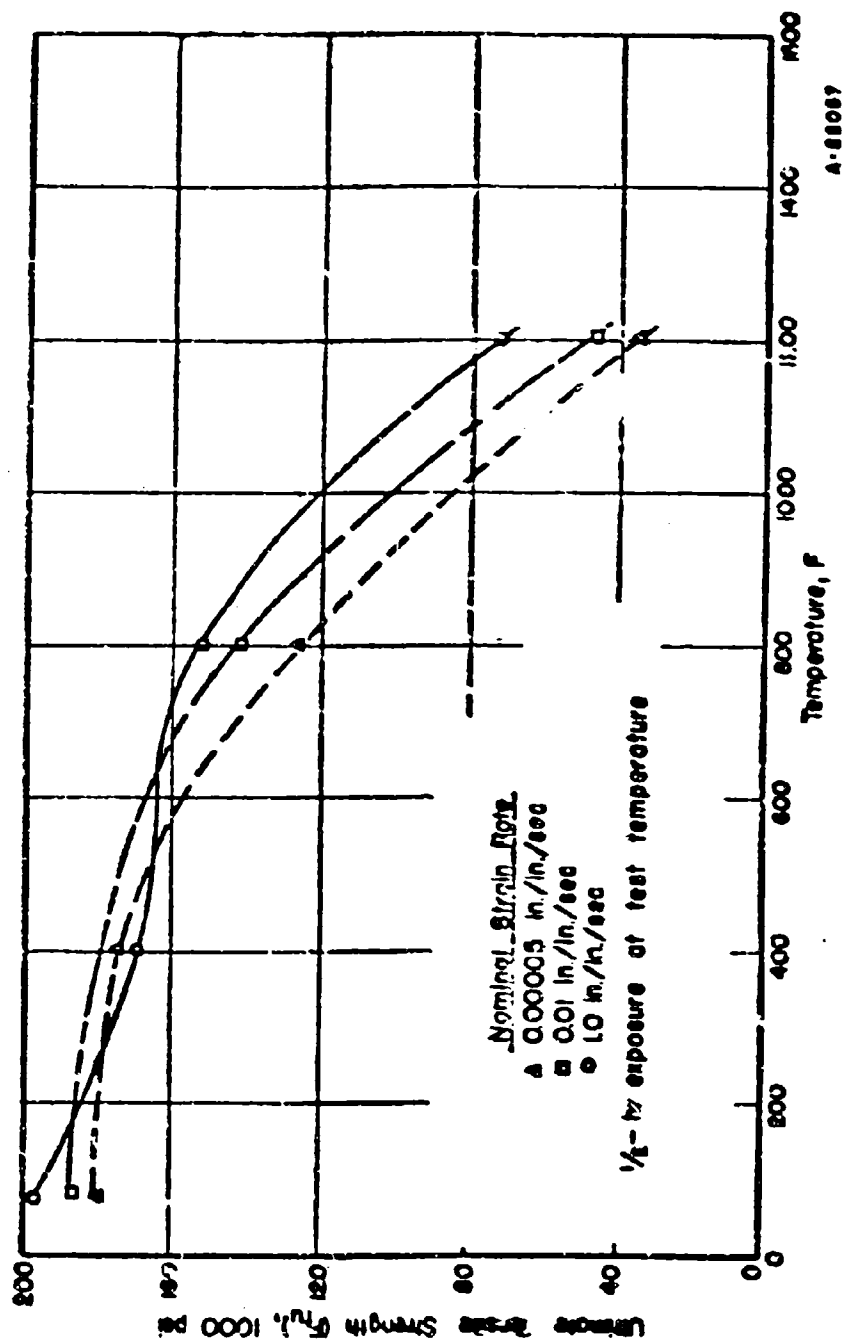


FIGURE 19. EFFECT OF STRAIN RATE ON TENSILE STRENGTH (F_u) OF 17-7PH (TH 1050) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. WADC 55-199, Part 2, p 74.

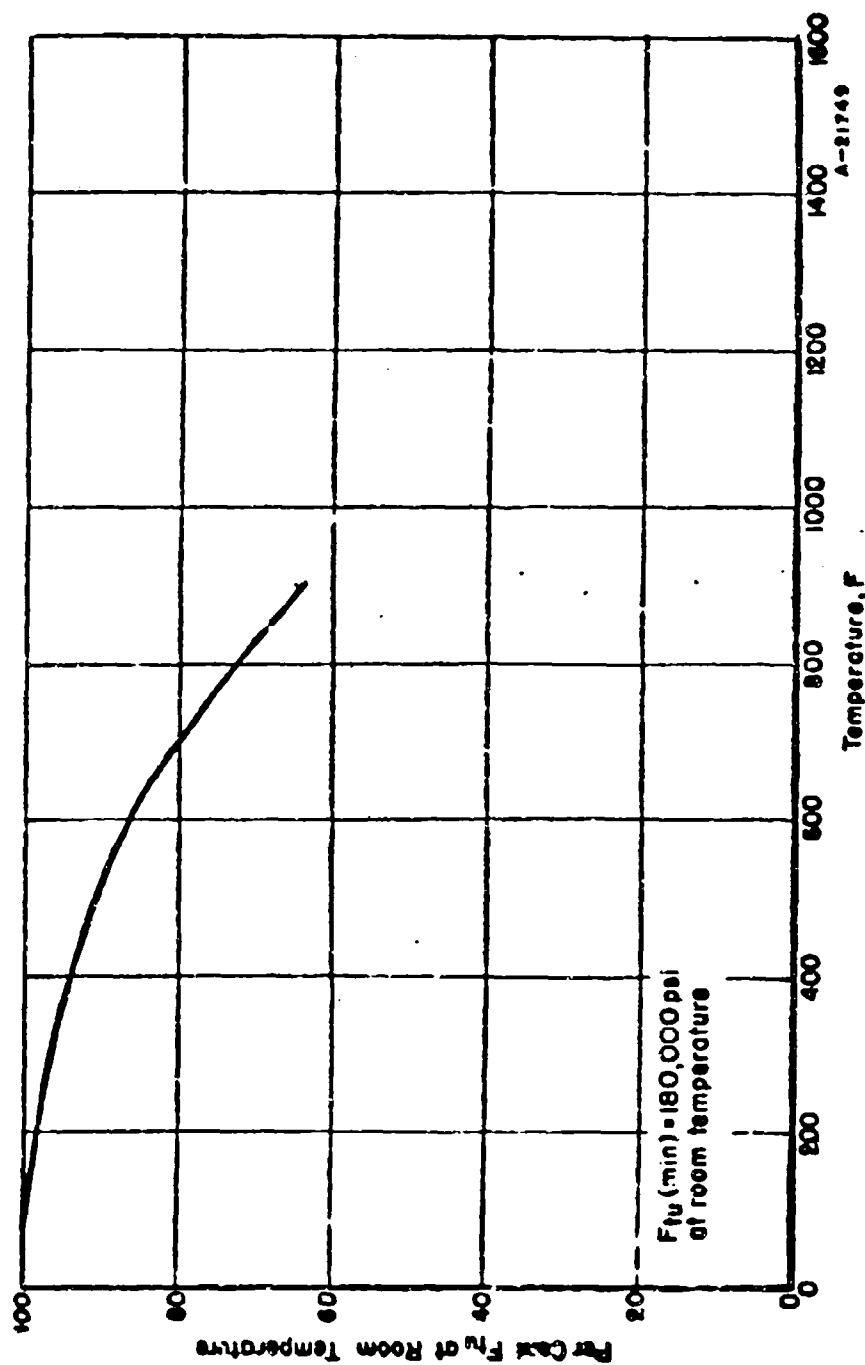


FIGURE 60. DESIGN CURVE FOR TENSILE STRENGTH (F_u) OF 17-7PH (TH 1050) STAINLESS STEEL AT ELEVATED TEMPERATURE

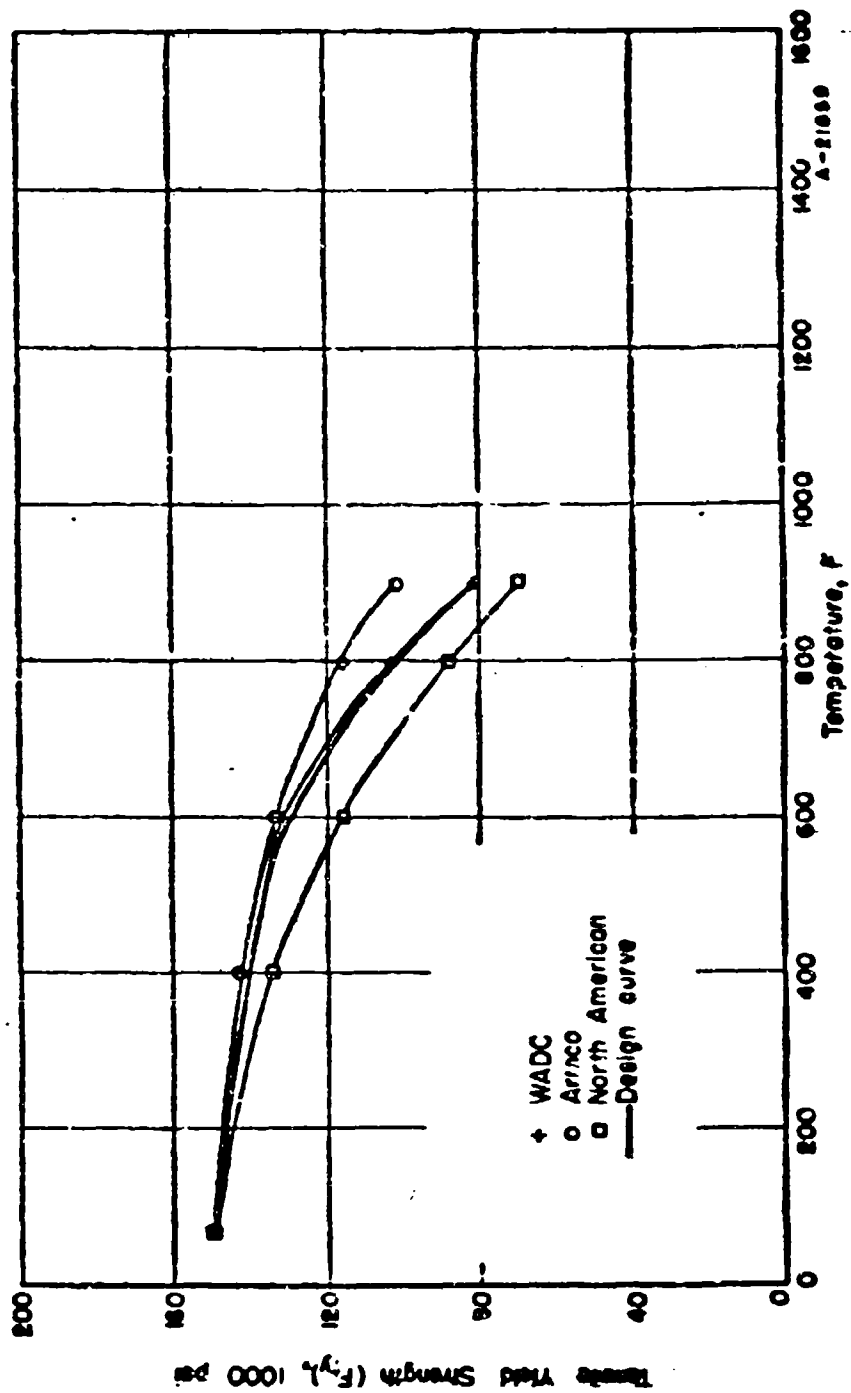


FIGURE 61. TENSILE YIELD STRENGTH (F_y) OF 17-7PH (TH 1050) STAINLESS STEEL AT ELEVATED TEMPERATURE

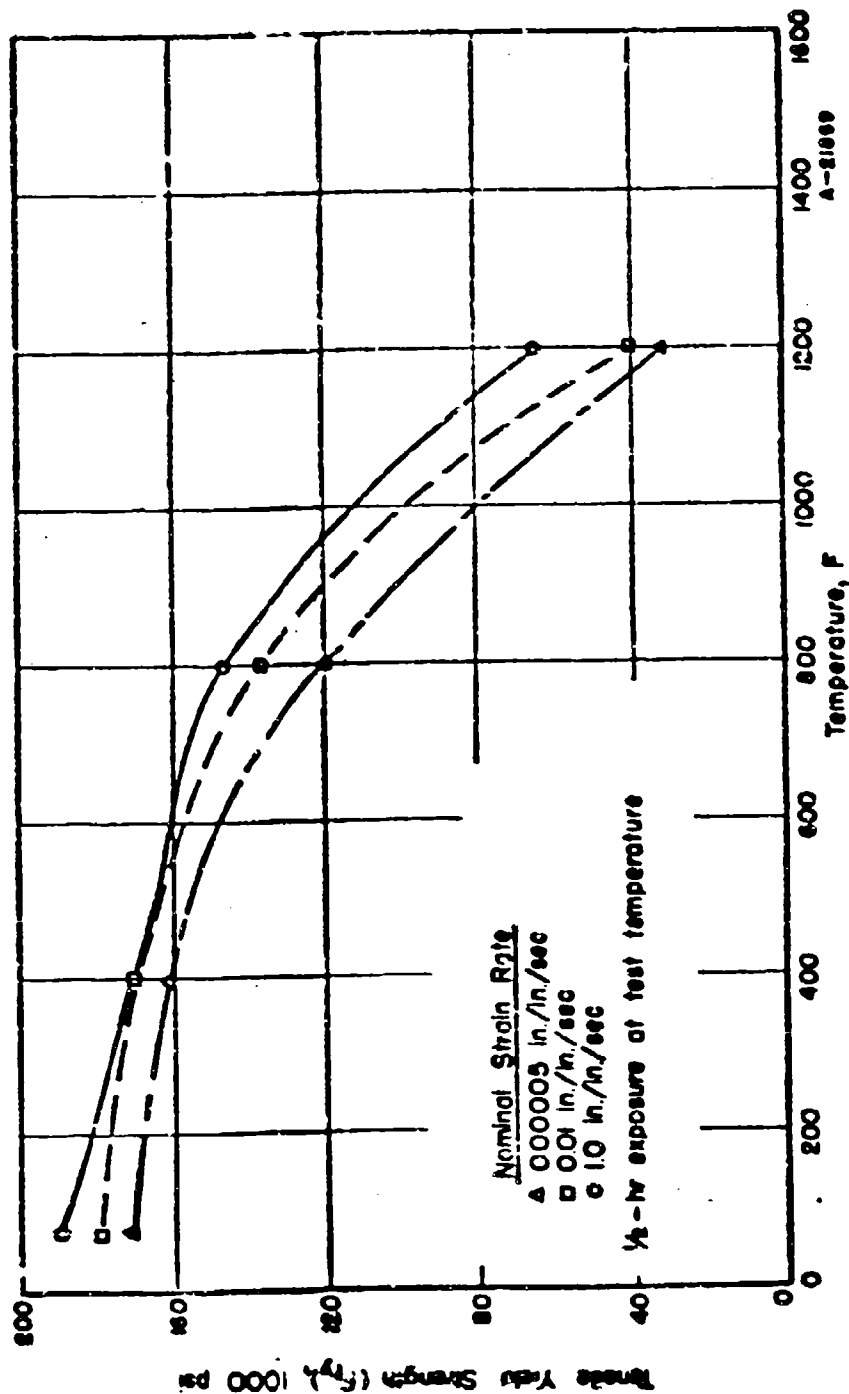


FIGURE 62. EFFECT OF STRAIN RATE ON THE TENSILE YIELD STRENGTH (F_y) OF 17-7PH (TH 1050) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. WADC 55-199, Part 2, p 74.

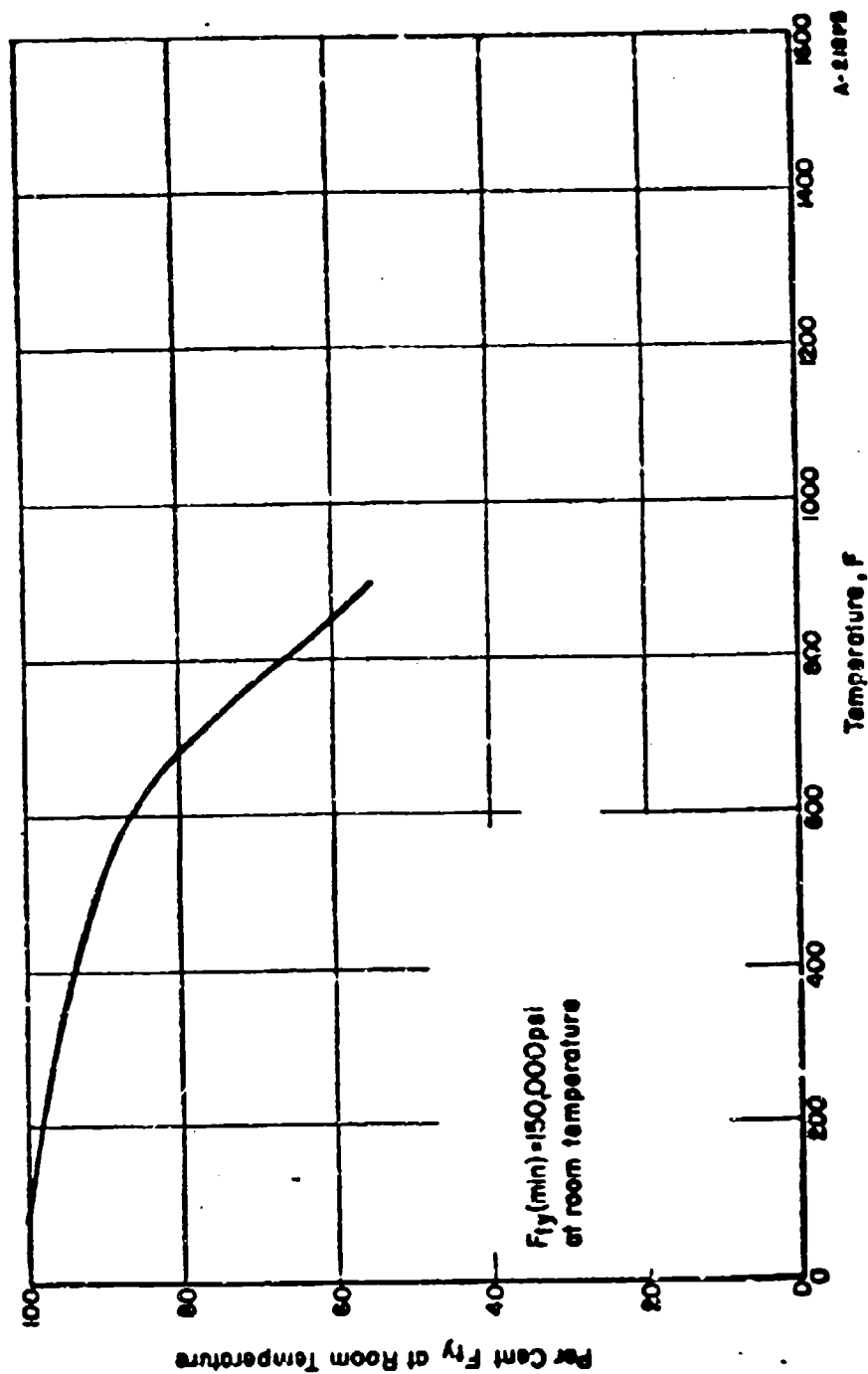


FIGURE 63. DESIGN CURVE FOR TENSILE YIELD STRENGTH (F_{ty}) OF 17-7PH (TH 1050) STAINLESS STEEL AT ELEVATED TEMPERATURE

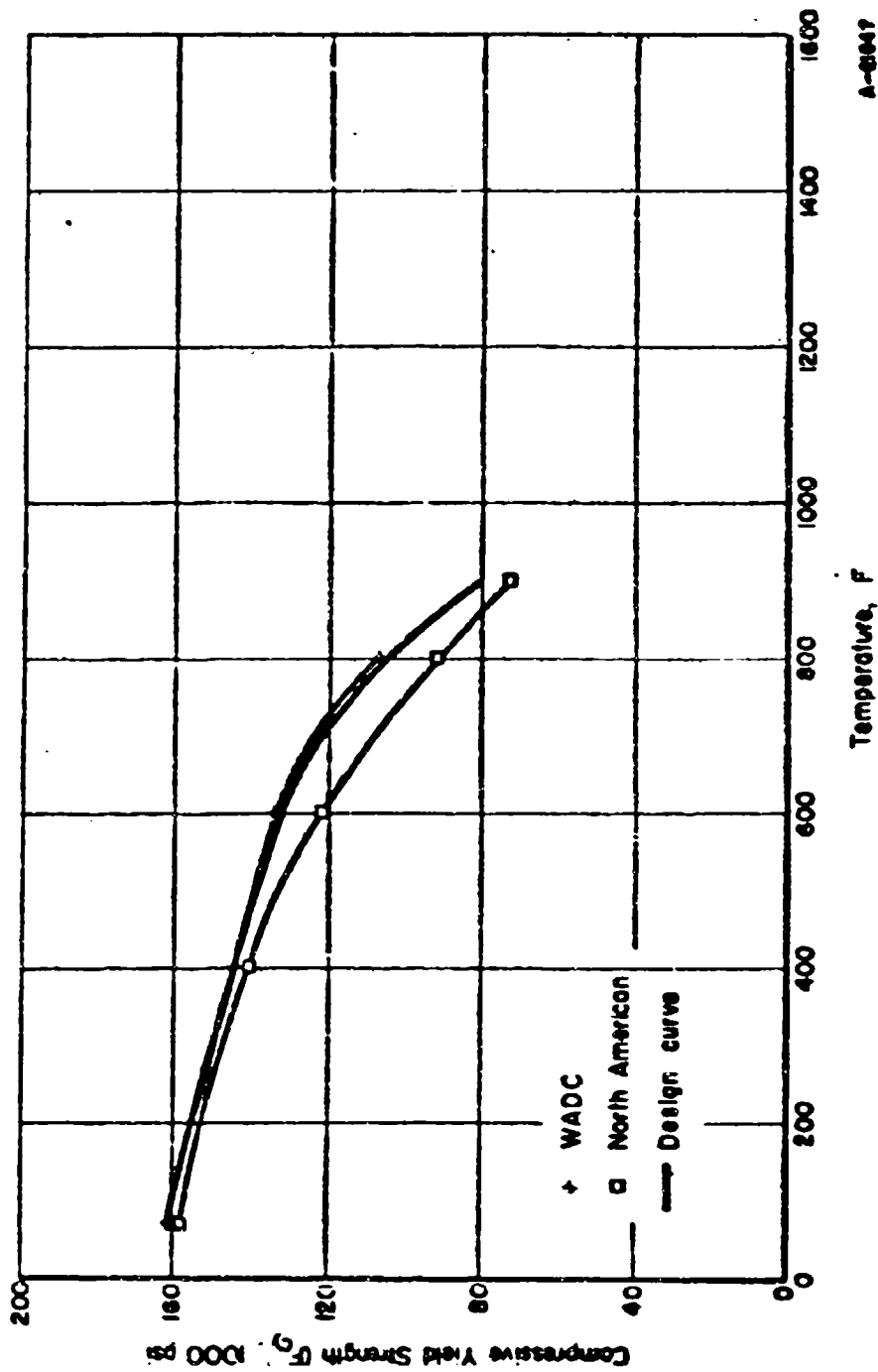


FIGURE 64. COMPRESSIVE YIELD STRENGTH (F_{cy}) OF 17-7PH (TH 1050) STAINLESS STEEL AT ELEVATED TEMPERATURE

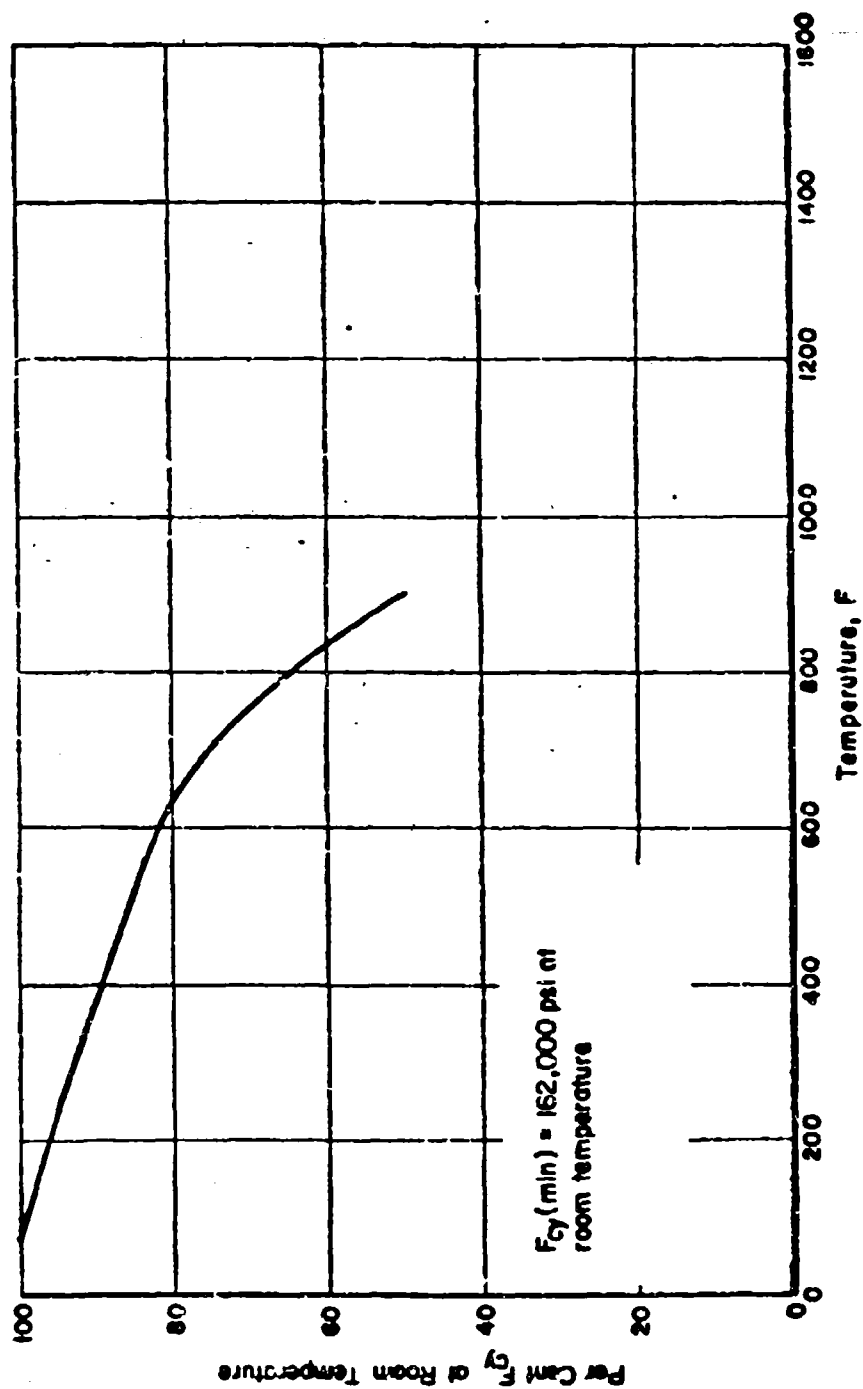


FIGURE 63. DESIGN CURVE FOR COMPRESSIVE YIELD STRENGTH (F_{cy}) OF 17-7PH (TH 1050) STAINLESS STEEL AT ELEVATED TEMPERATURE

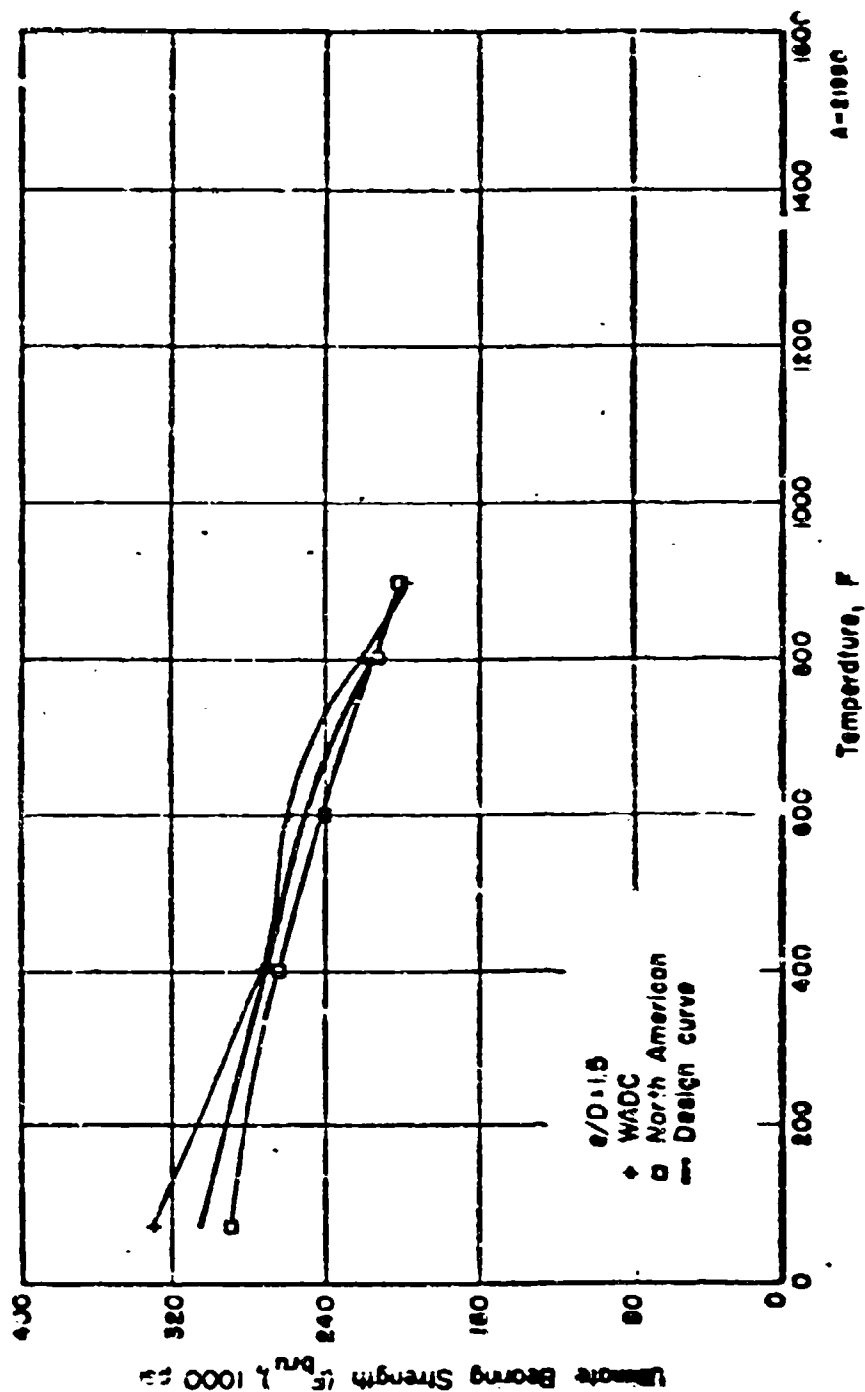


FIGURE 66. BEARING STRENGTH (F_{bu}) OF 17-7PH (TI 1030) STAINLESS STEEL AT ELEVATED TEMPERATURE

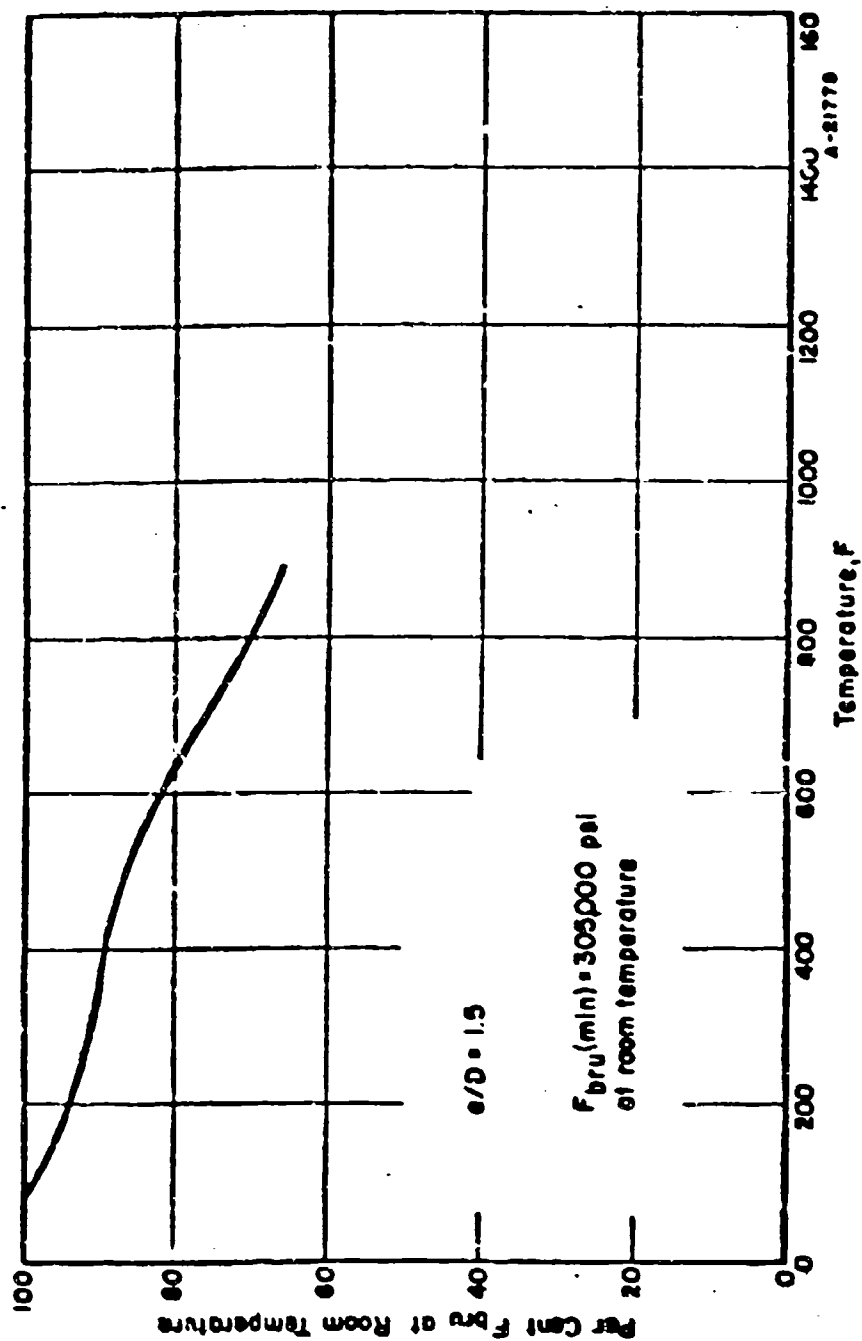


FIGURE 67. DESIGN CURVE FOR BEARING STRENGTH (F_{bru}) OF 17-7PH (TH 1050) STAINLESS STEEL AT ELEVATED TEMPERATURE

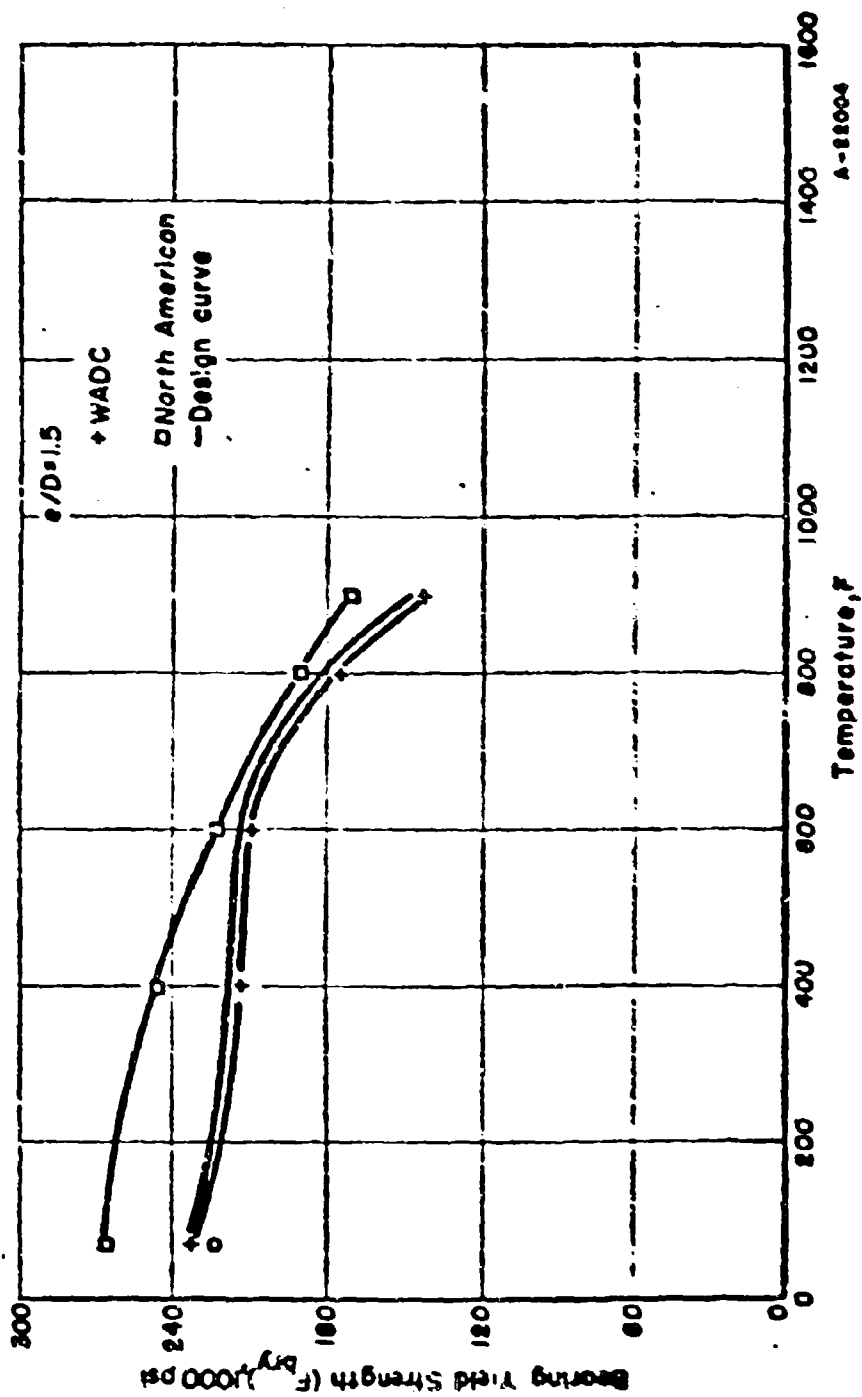


FIGURE 68. BEARING YIELD STRENGTH (F_{bry}) OF 17-7PH (TH 1050) STAINLESS STEEL AT ELEVATED TEMPERATURE

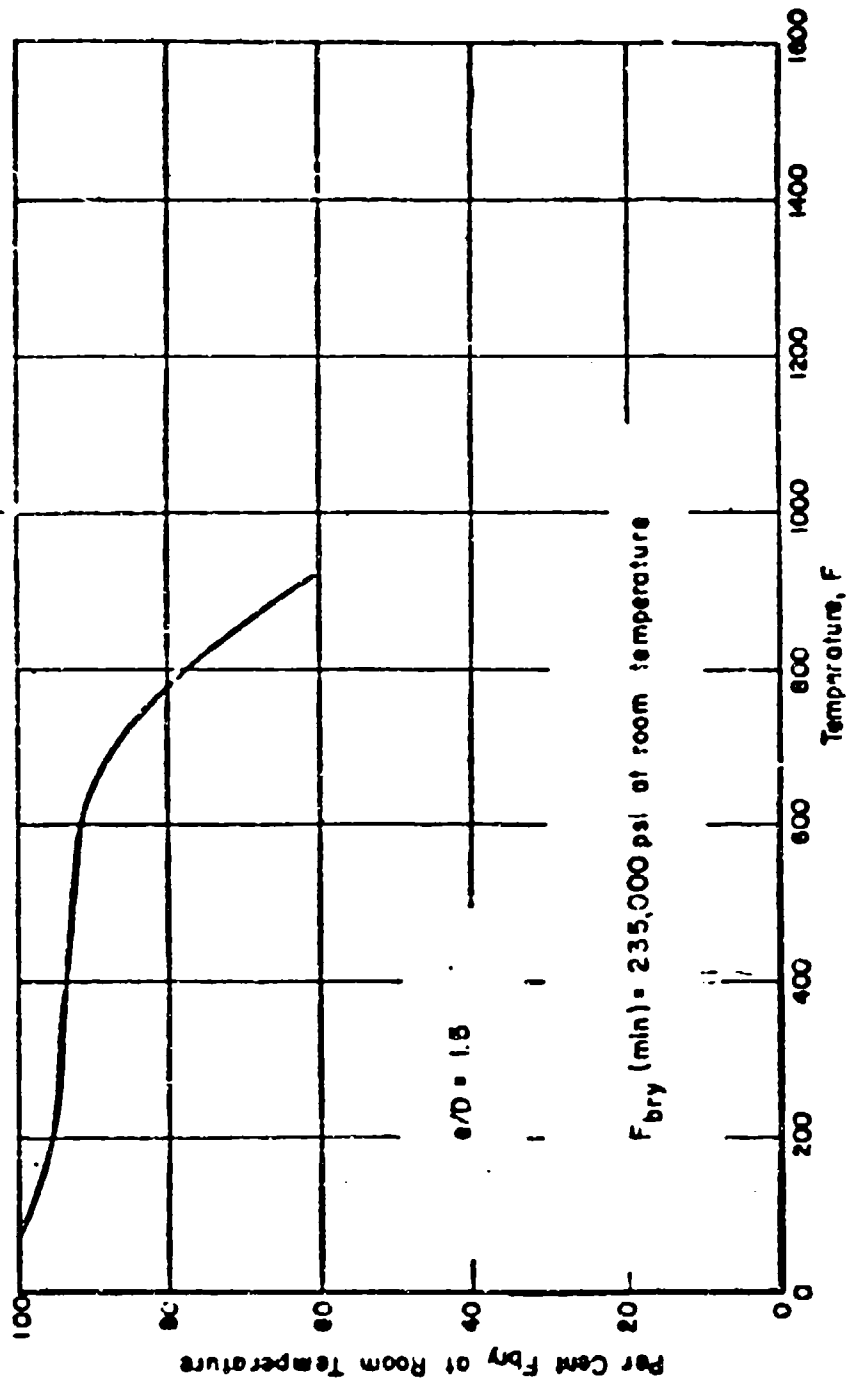


FIGURE 69. DESIGN CURVE FOR BEARING YIELD STRENGTH (F_{bry}) OF 17-7PH (TH 1050) STAINLESS STEEL AT ELEVATED TEMPERATURE

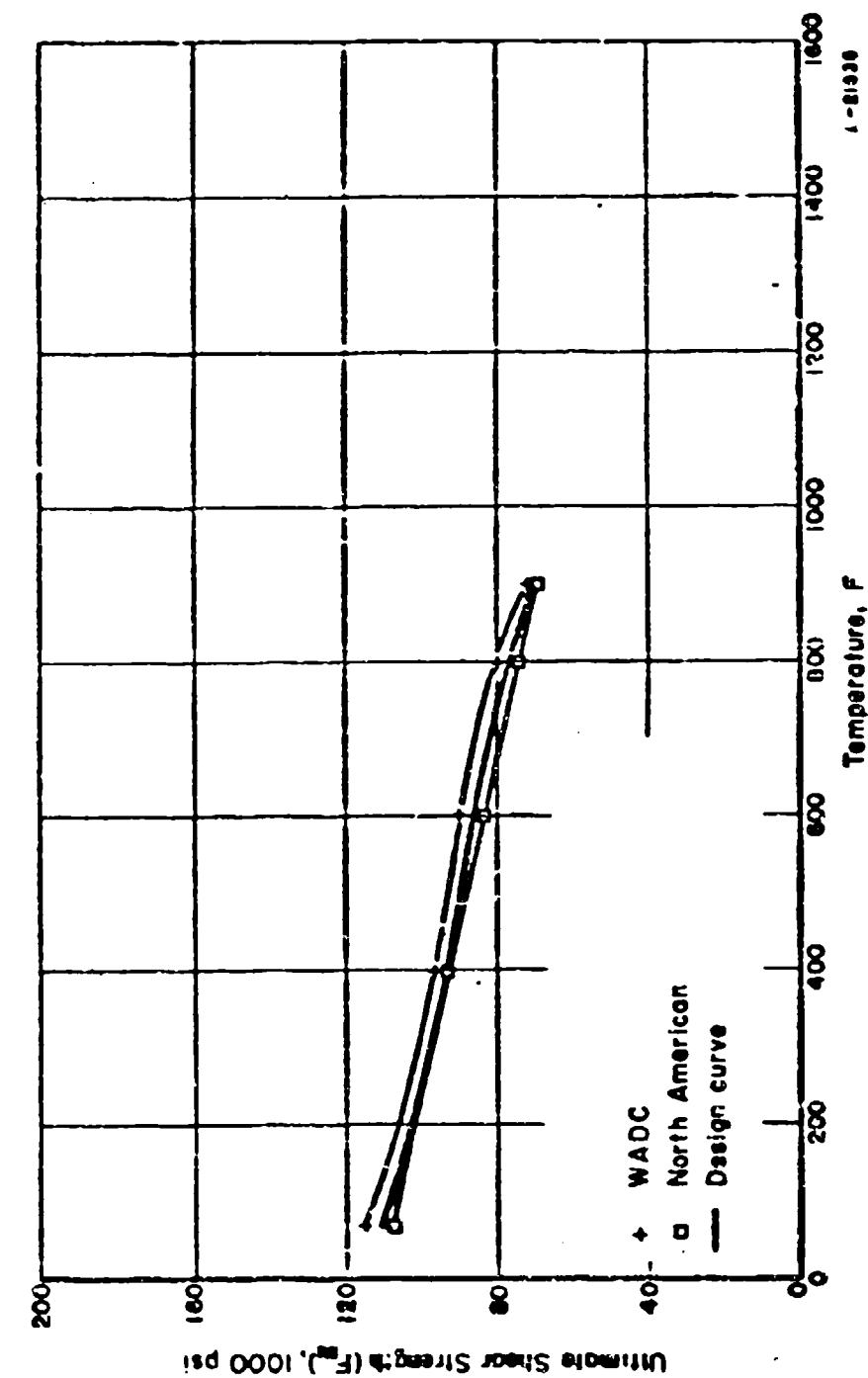


FIGURE 70. SHEAR STRENGTH (F_{su}) OF 17-7PH (TH 1050) STAINLESS STEEL AT ELEVATED TEMPERATURE

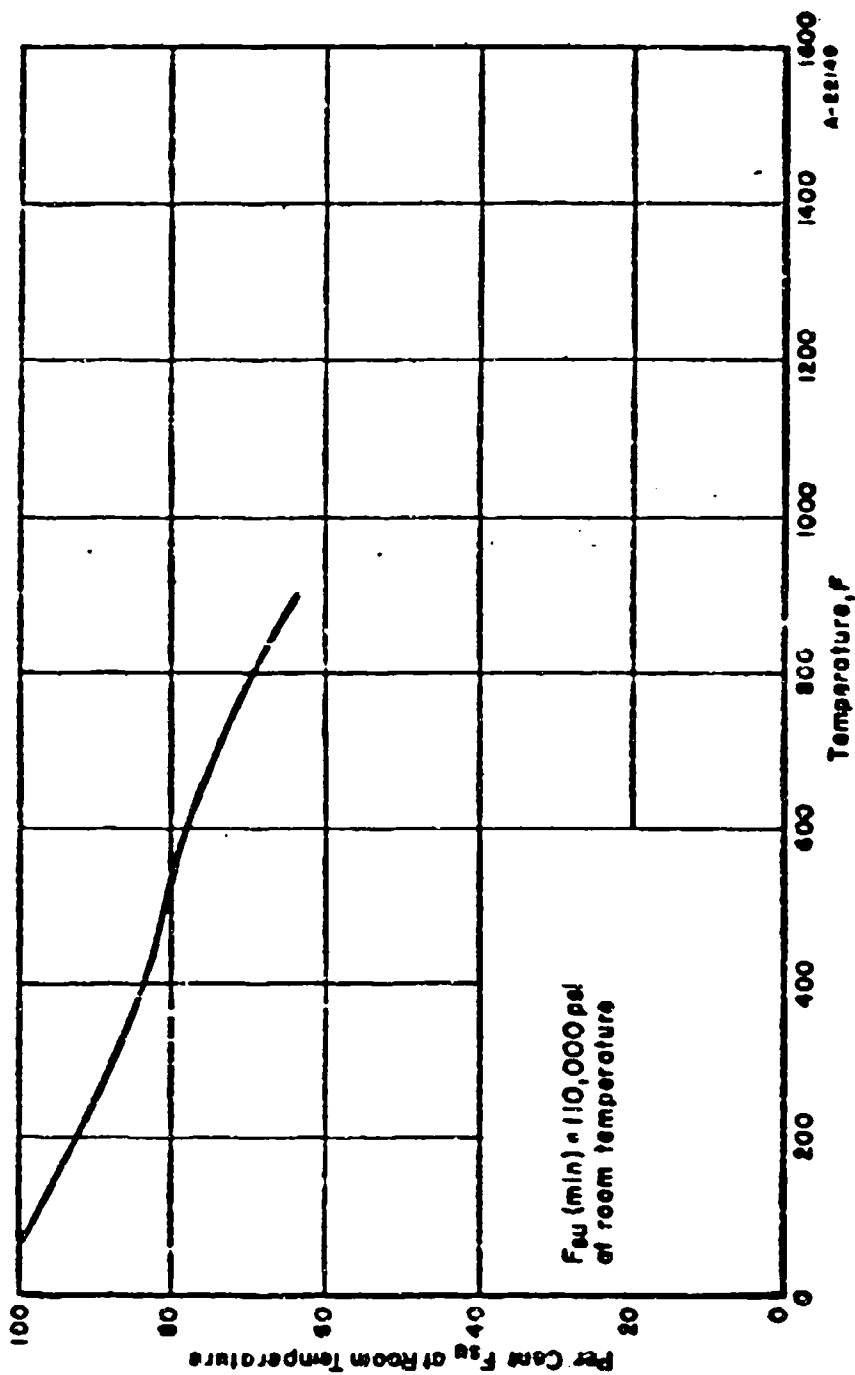


FIGURE 71. DESIGN CURVE FOR SHEAR STRENGTH (F_{su}) OF 17-7PH (TH 1050) STAINLESS STEEL AT ELEVATED TEMPERATURE

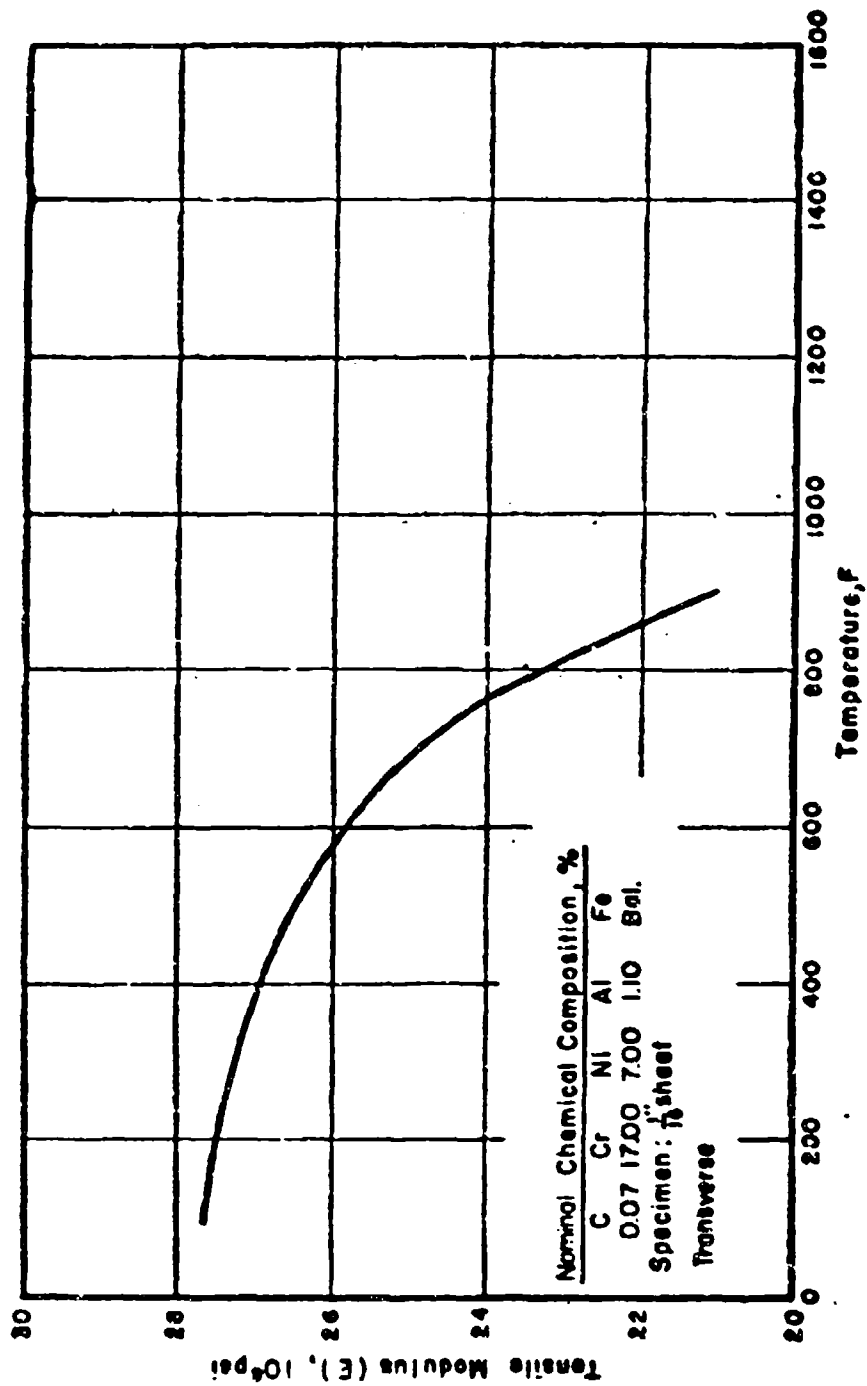


FIGURE 72. TENSILE MODULUS (E) OF 17-7PH (TH 1050) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 356.

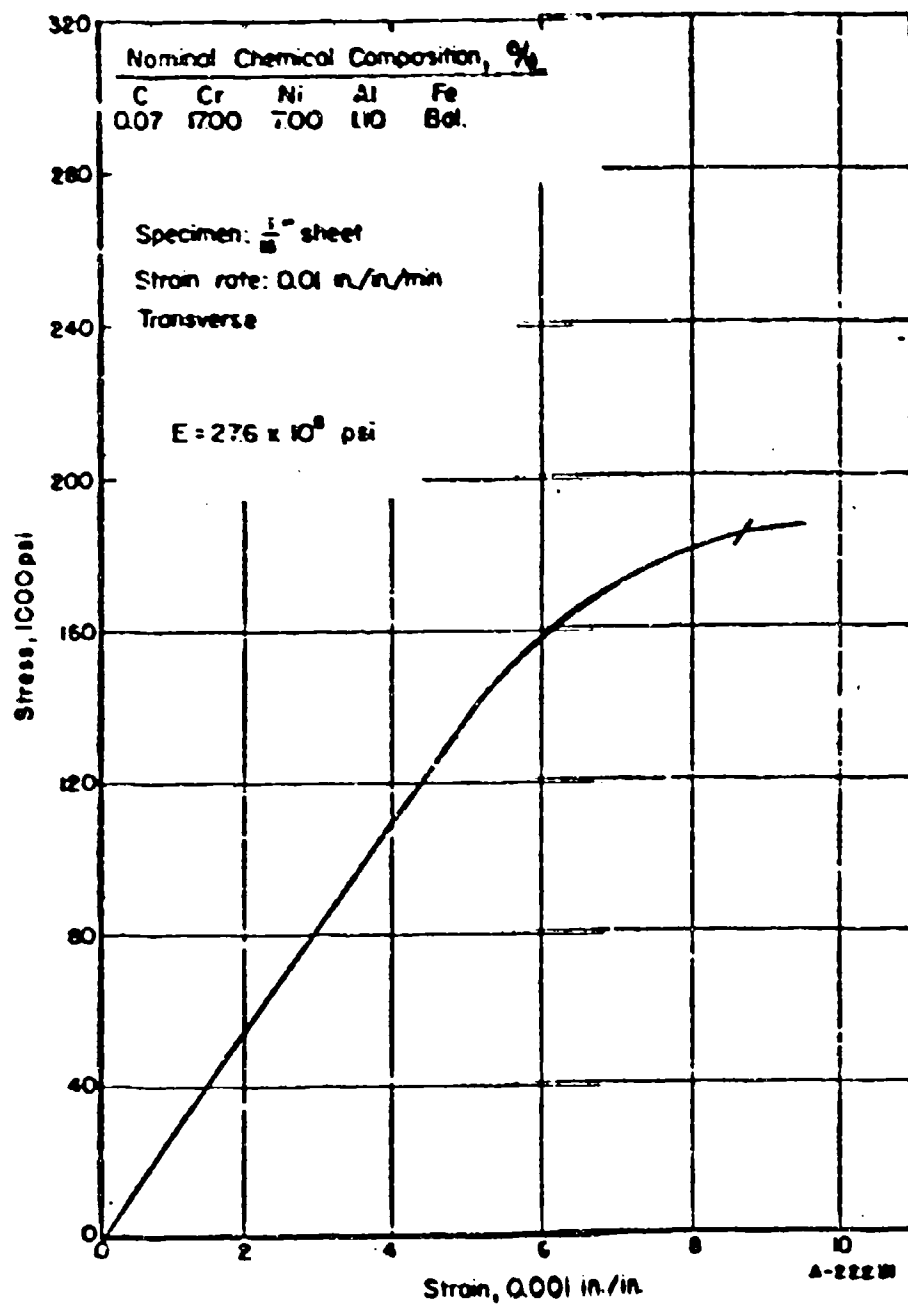


FIGURE 73. TENSILE STRESS-STRAIN CURVE FOR 17-7PH (Type 1050) STAINLESS STEEL AT ROOM TEMPERATURE

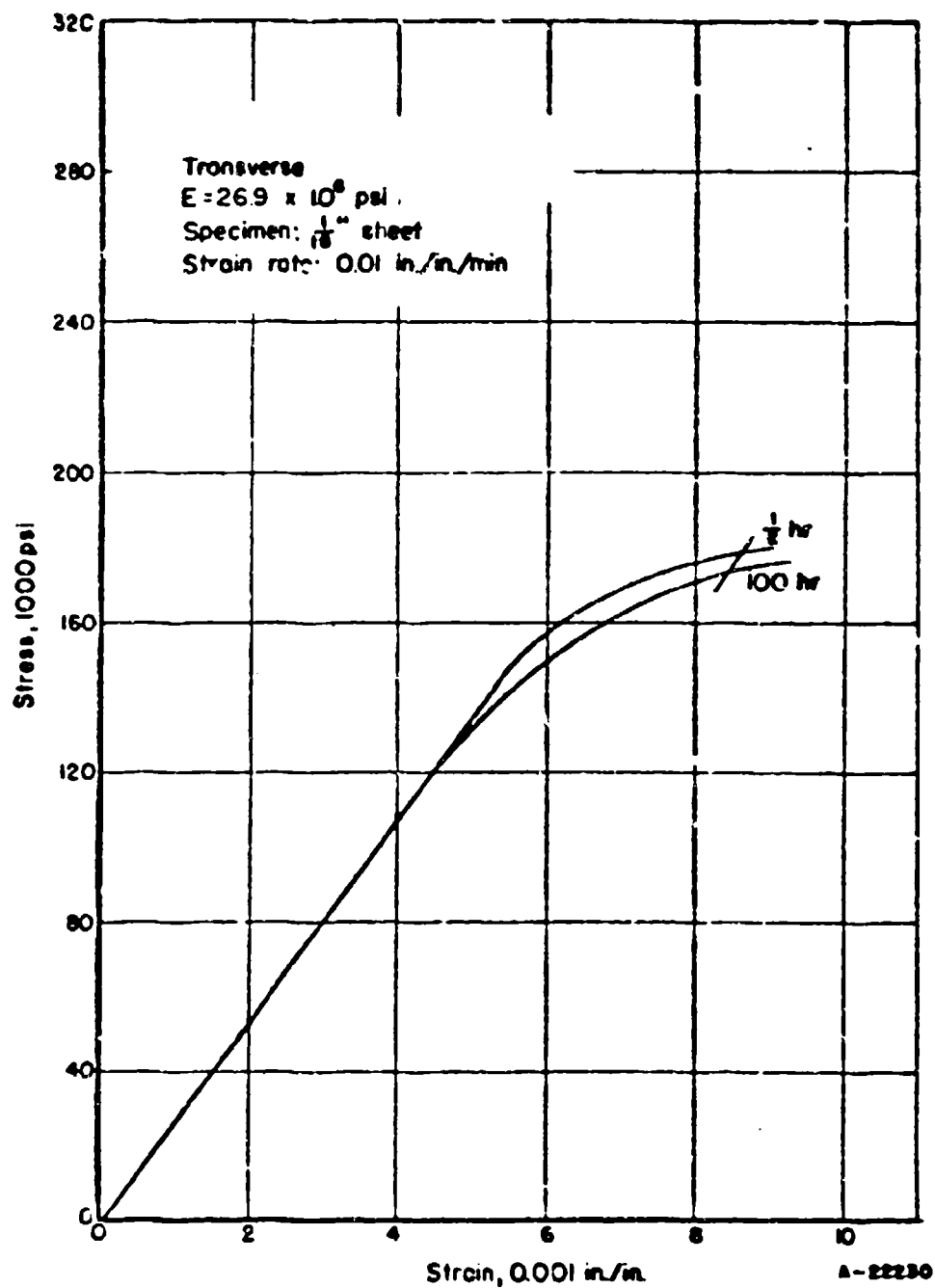


FIGURE 74. TENSILE STRESS-STRAIN CURVES FOR 17-7PH
 (TH 2450) STAINLESS STEEL AT 400 F

Ref. 356.

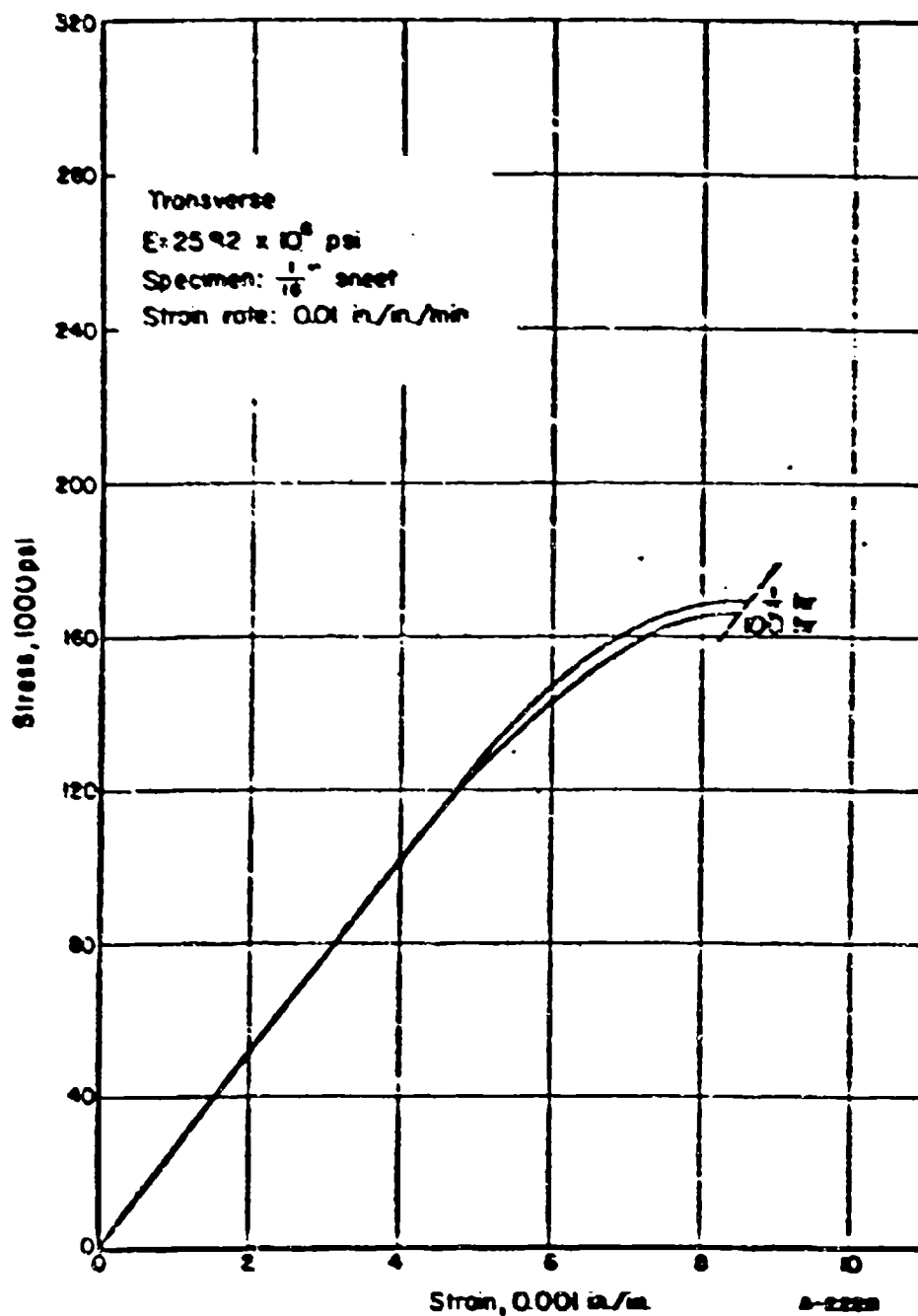


FIGURE 75. TENSILE STRESS-STRAIN CURVES FOR 17-7PH (TH 1050) STAINLESS STEEL AT 600 F

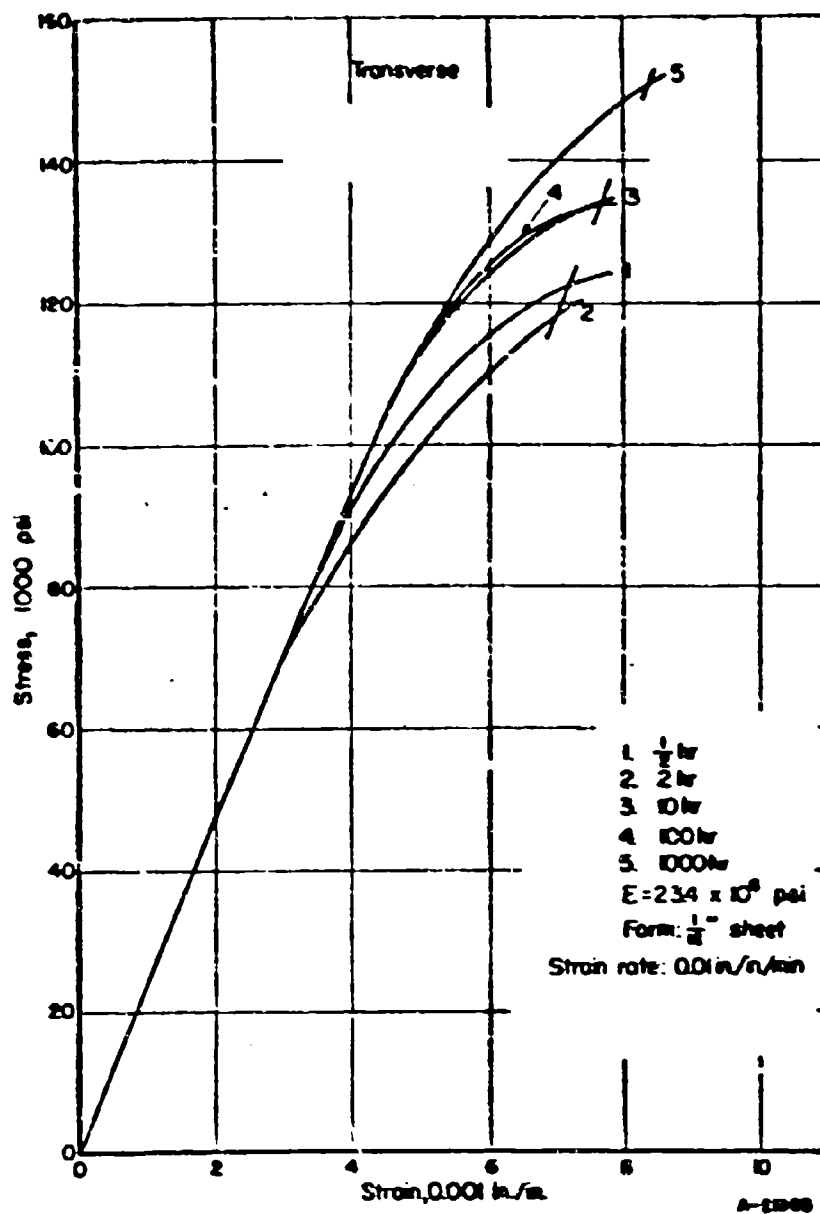


FIGURE 76. TENSILE STRESS-STRAIN CURVES FOR 17-7PH (TH 1050) STAINLESS STEEL AT 800 F

Ref. 356.

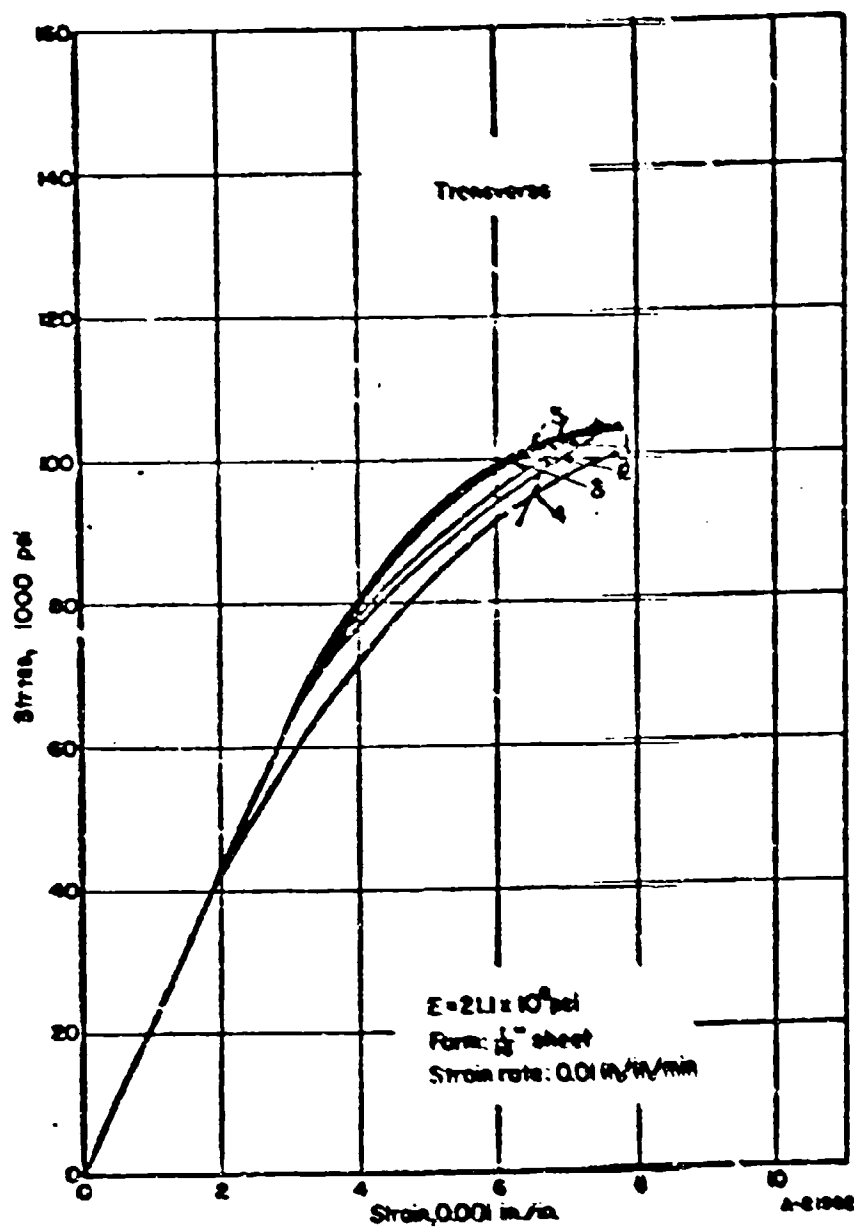


FIGURE 77. TENSILE STRESS-STRAIN CURVES FOR 17-7PH (TH 1050) STAINLESS STEEL AT 900 F

Ref. 354.

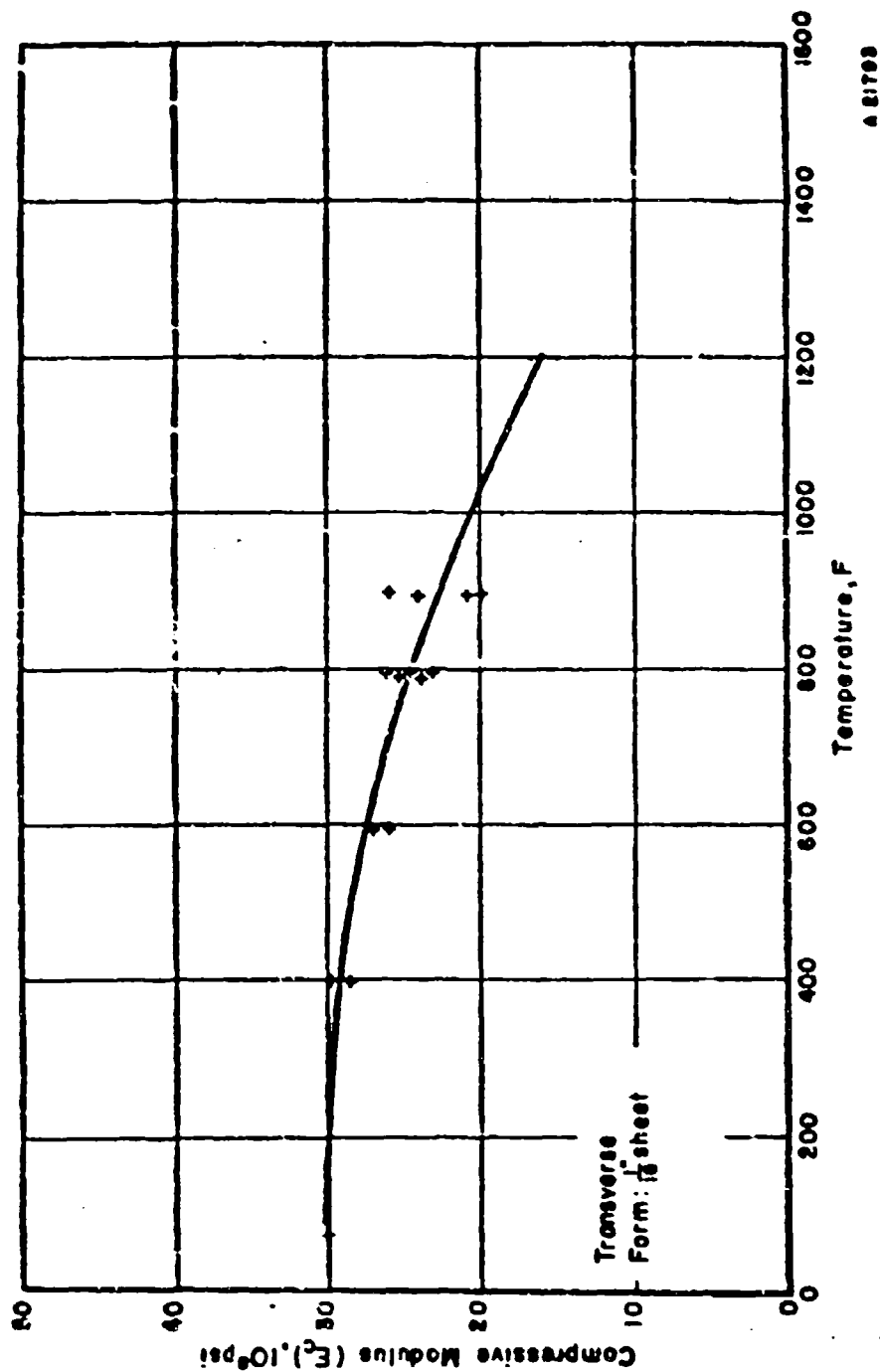


FIGURE 78. COMPRESSIVE MODULUS (E_c) OF 17-7PH (TH 1050) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 356.

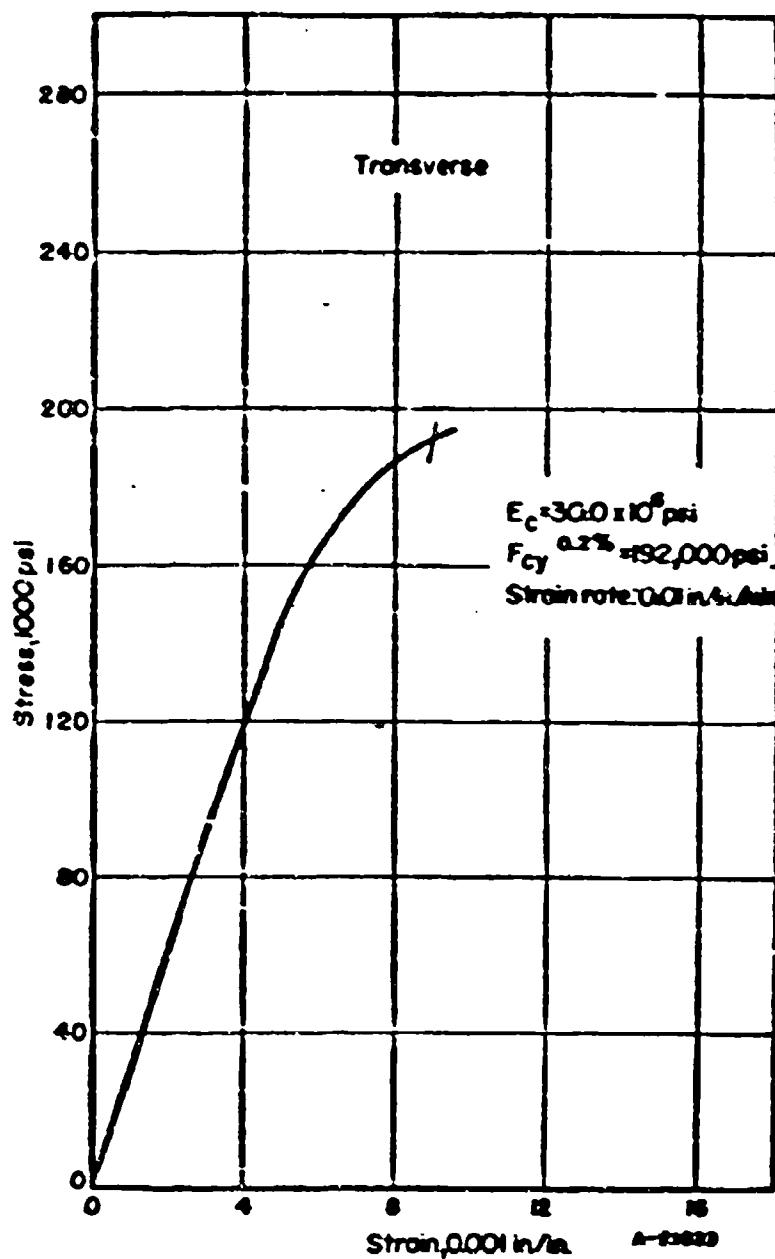


FIGURE 79. COMPRESSIVE STRESS-STRAIN CURVE FOR 17-7PH (Ti 1050) STAINLESS STEEL AT ROOM TEMPERATURE

Ref. 35A

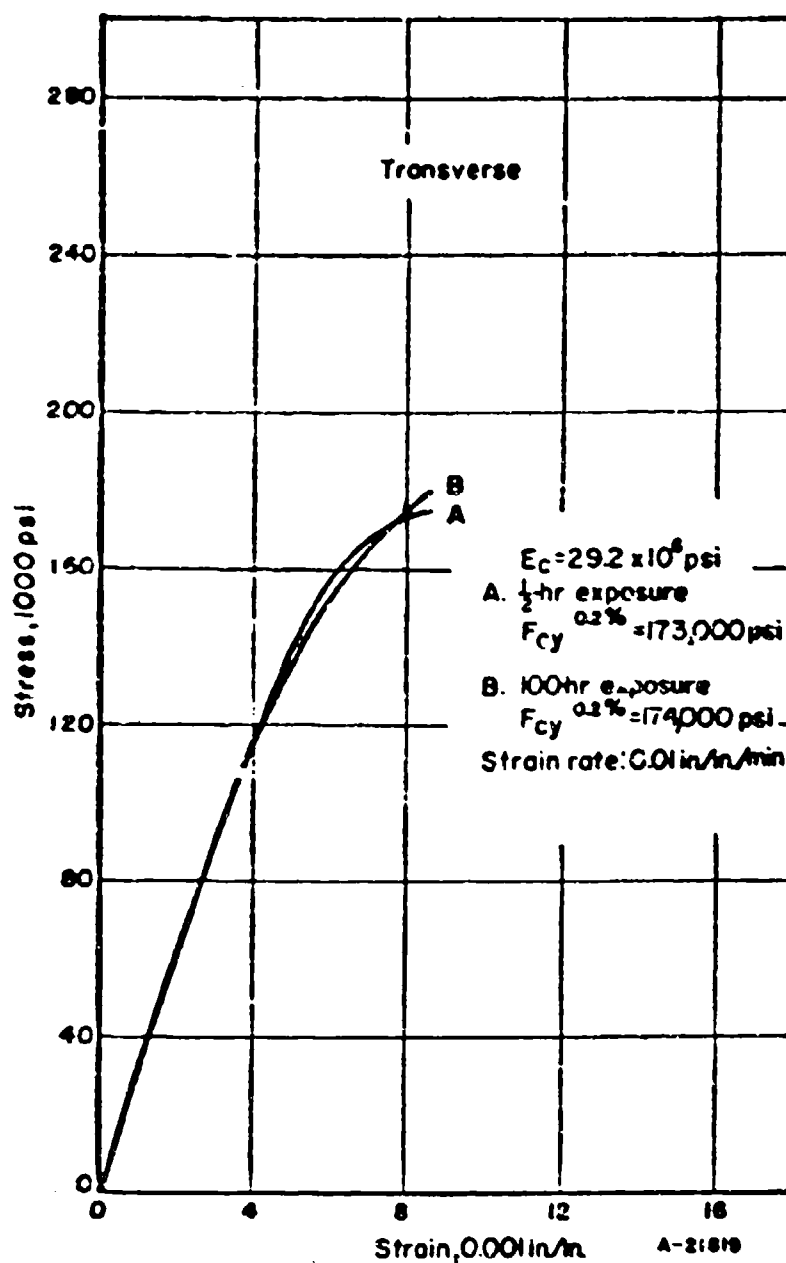


FIGURE 80. COMPRESSIVE STRESS-STRAIN CURVES FOR 17-7PH (TH 1050) STAINLESS STEEL AT 400 F

Ref. 356.

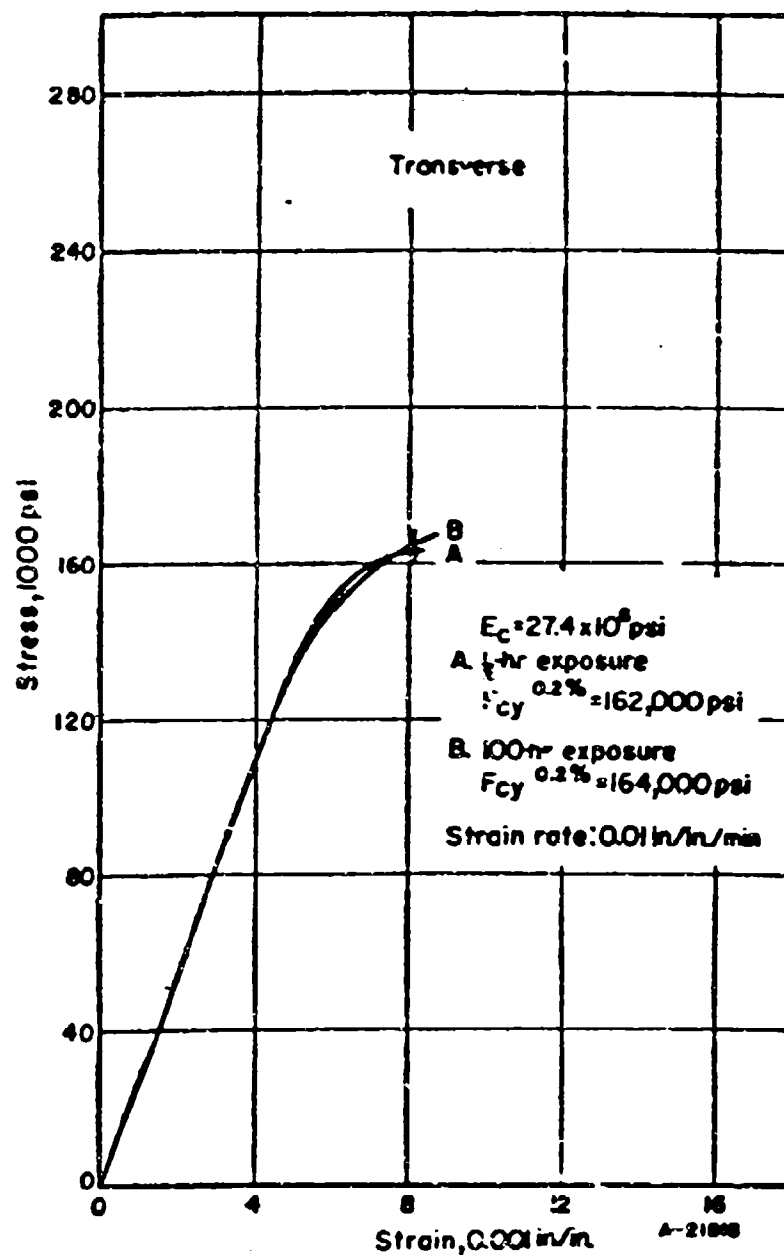


FIGURE 81. COMPRESSIVE STRESS-STRAIN CURVES FOR 17-7PH (TH 10.0) STAINLESS STEEL AT 600 F

Ref. 356.

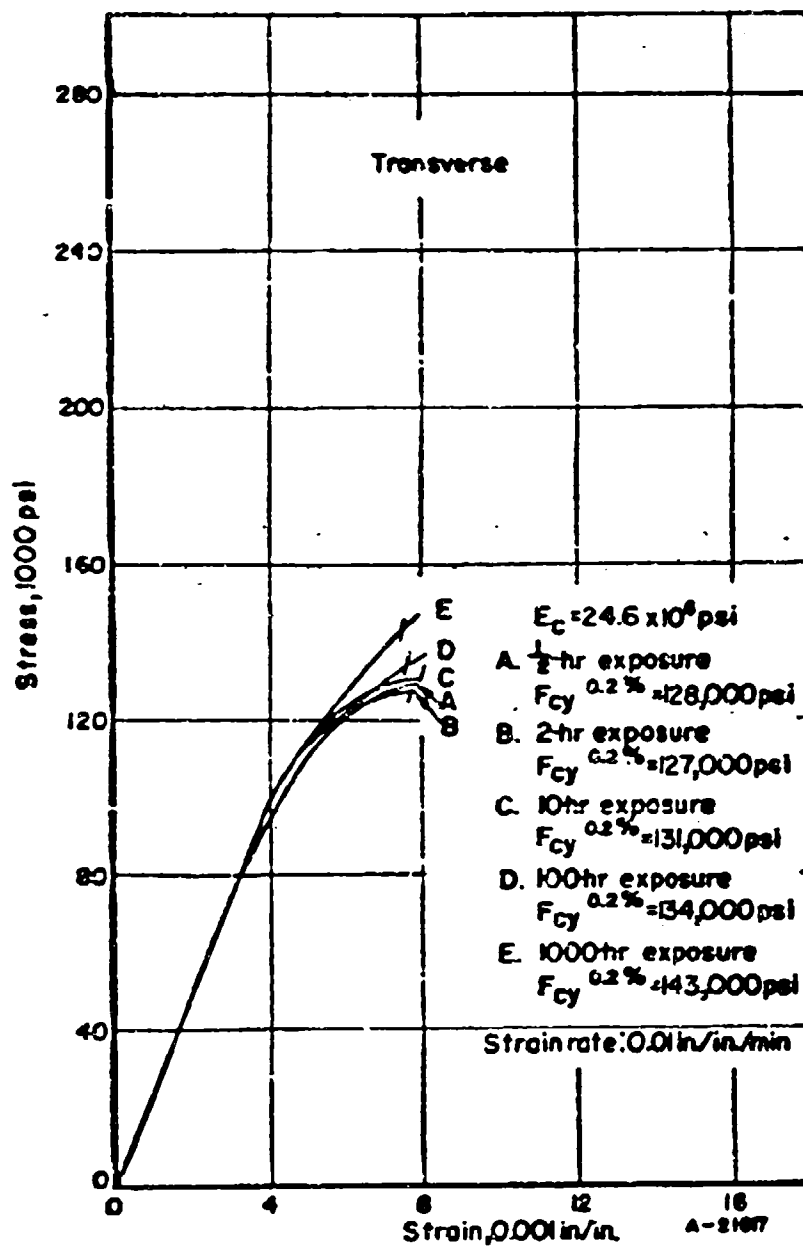


FIGURE 62. COMPRESSIVE STRESS-STRAIN CURVES FOR 17-7PH (TH 1050) STAINLESS STEEL AT 800 F

Ref. 356.

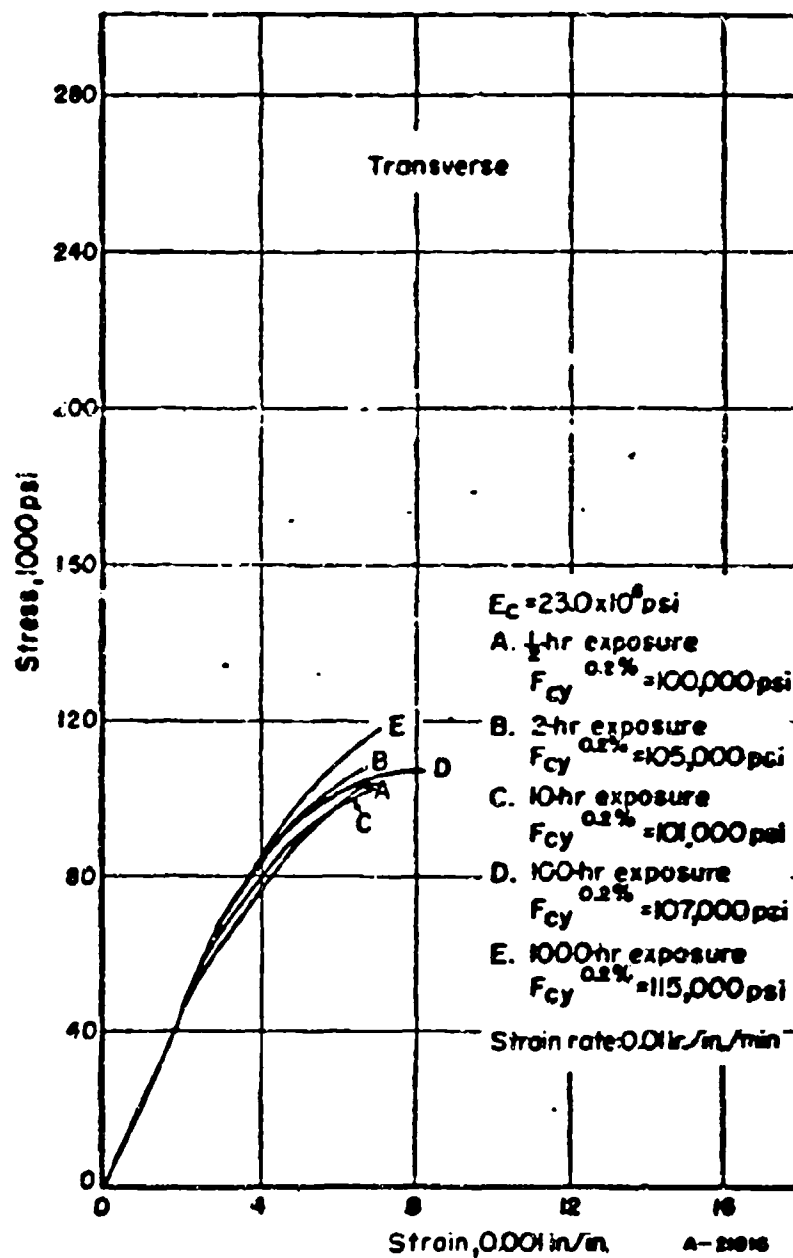
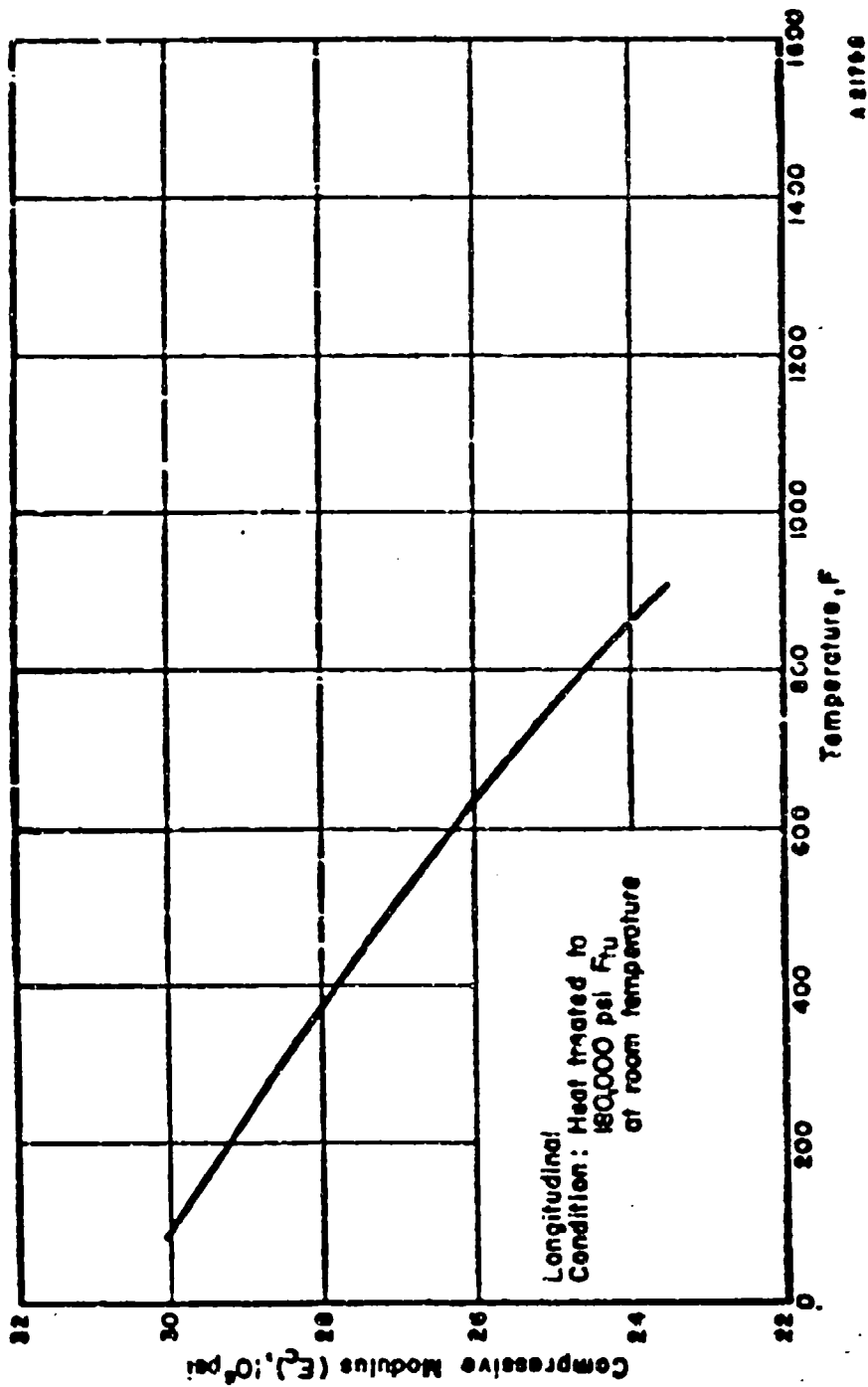


FIGURE 83. COMPRESSIVE STRESS-STRAIN CURVES FOR 17-7PH (TH 1050) STAINLESS STEEL AT 900 F

Ref. 356.



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FIGURE 84. COMPRESSIVE MODULUS (E_c) OF 17-7PH STAINLESS STEEL
AT ELEVATED TEMPERATURE

Ref. 207.

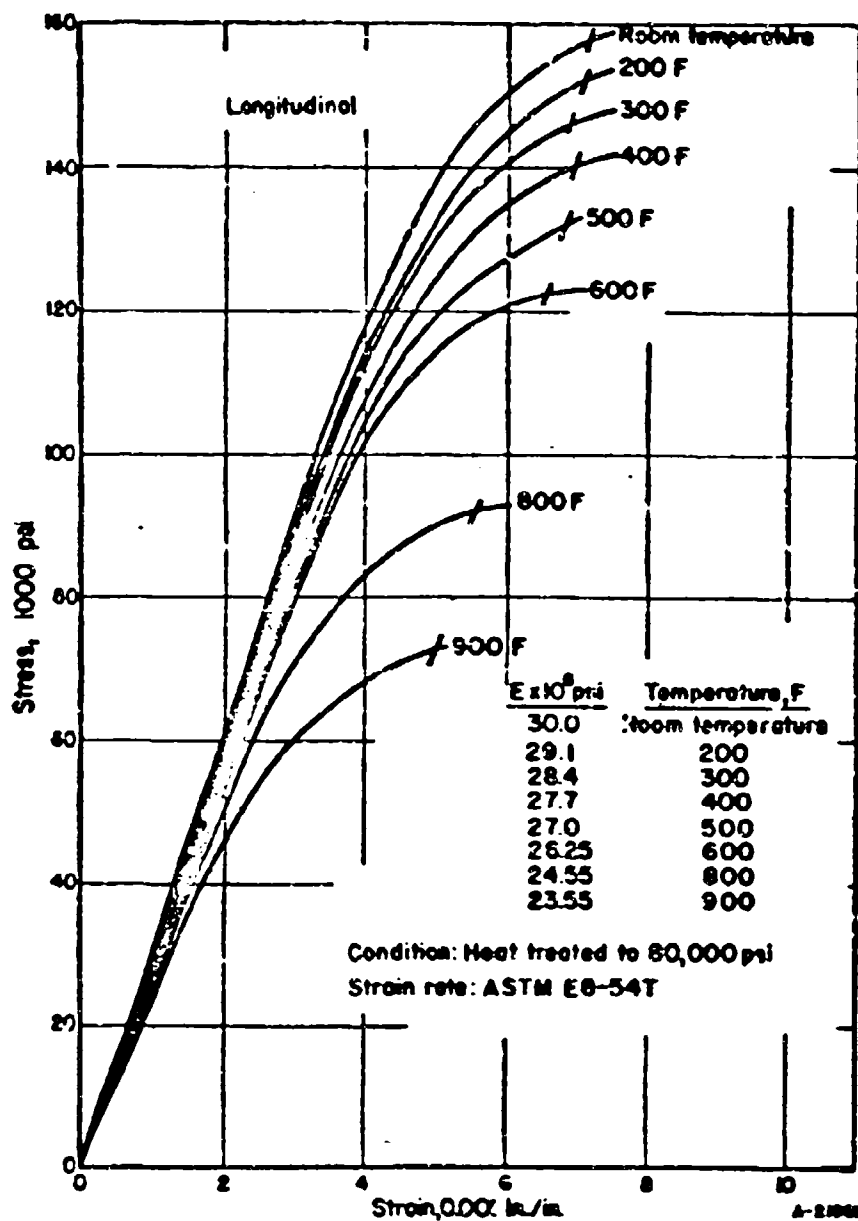


FIGURE 85. COMPRESSIVE STRESS STRAIN CURVES FOR 17-7PH STAINLESS STEEL AT ROOM AND ELEVATED TEMPERATURES

Ref. 207.

WADC TR 55-150 Pt 5

97

5

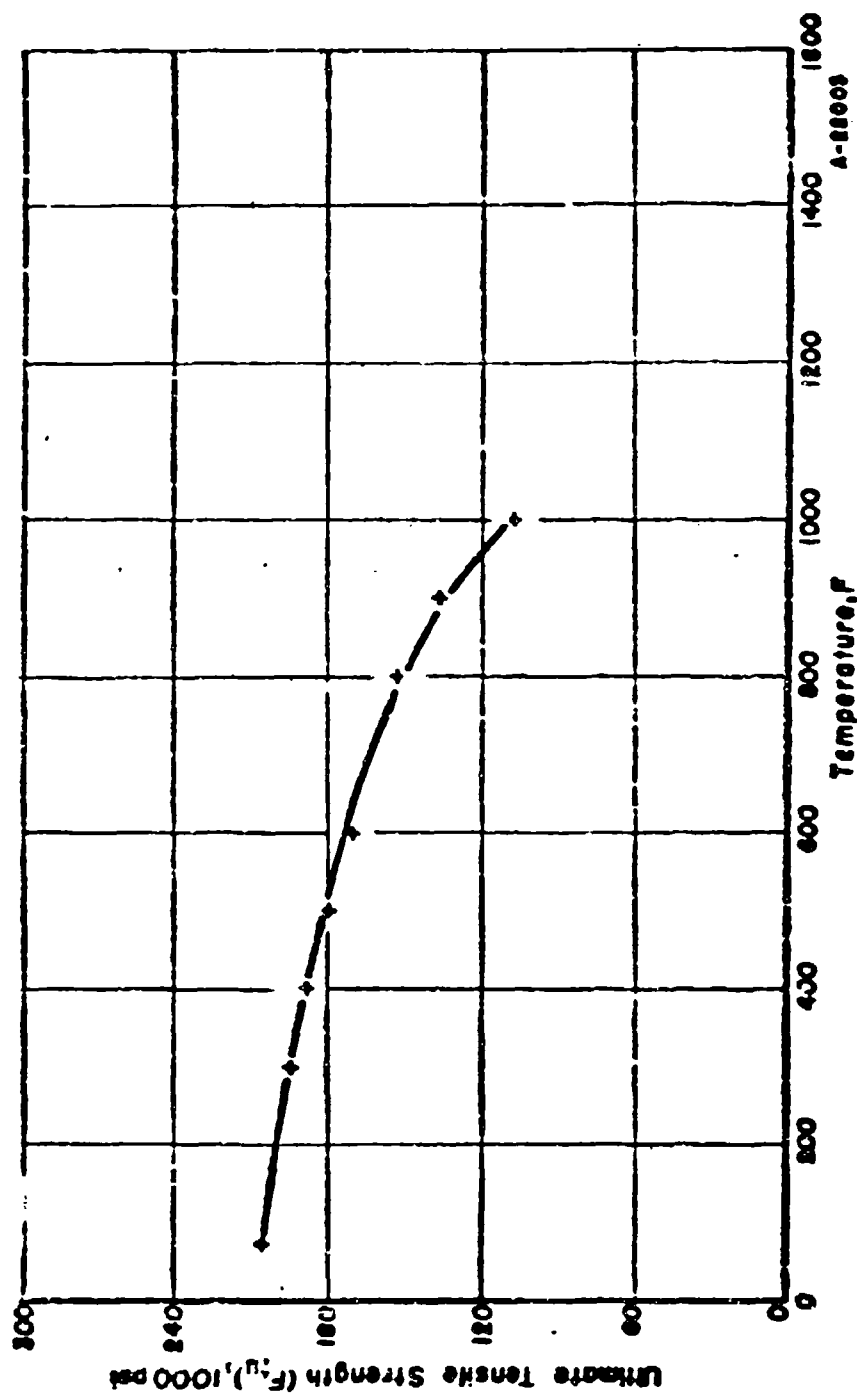


FIGURE 86. TENSILE STRENGTH (F_u) OF 17-7PH (TH 950) STAINLESS STEEL AT ELEVATED TEMPERATURE

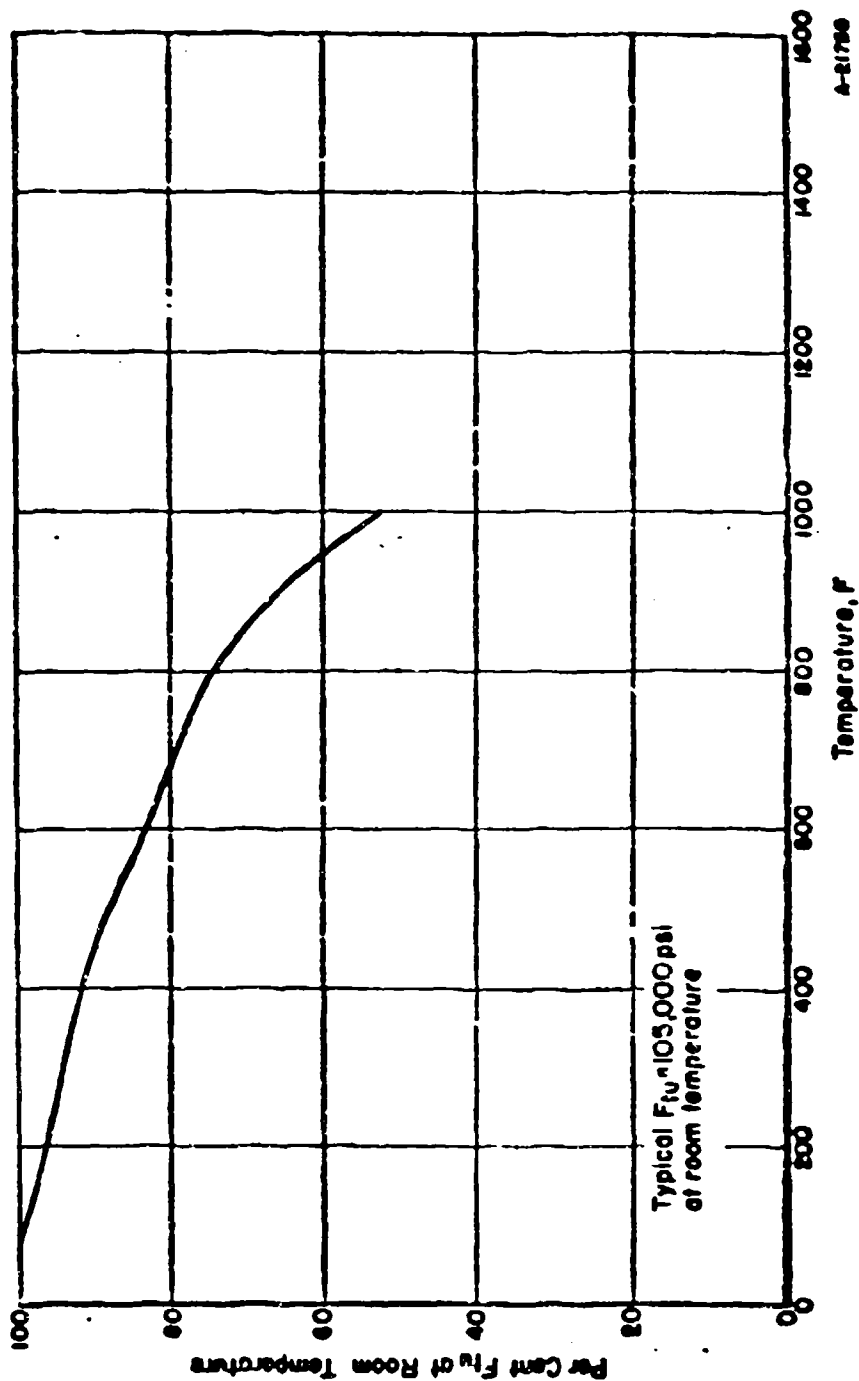


FIGURE 87. DESIGN CURVE FOR TENSILE STRENGTH (F_u) OF 17-7PH (TH 950) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 215.

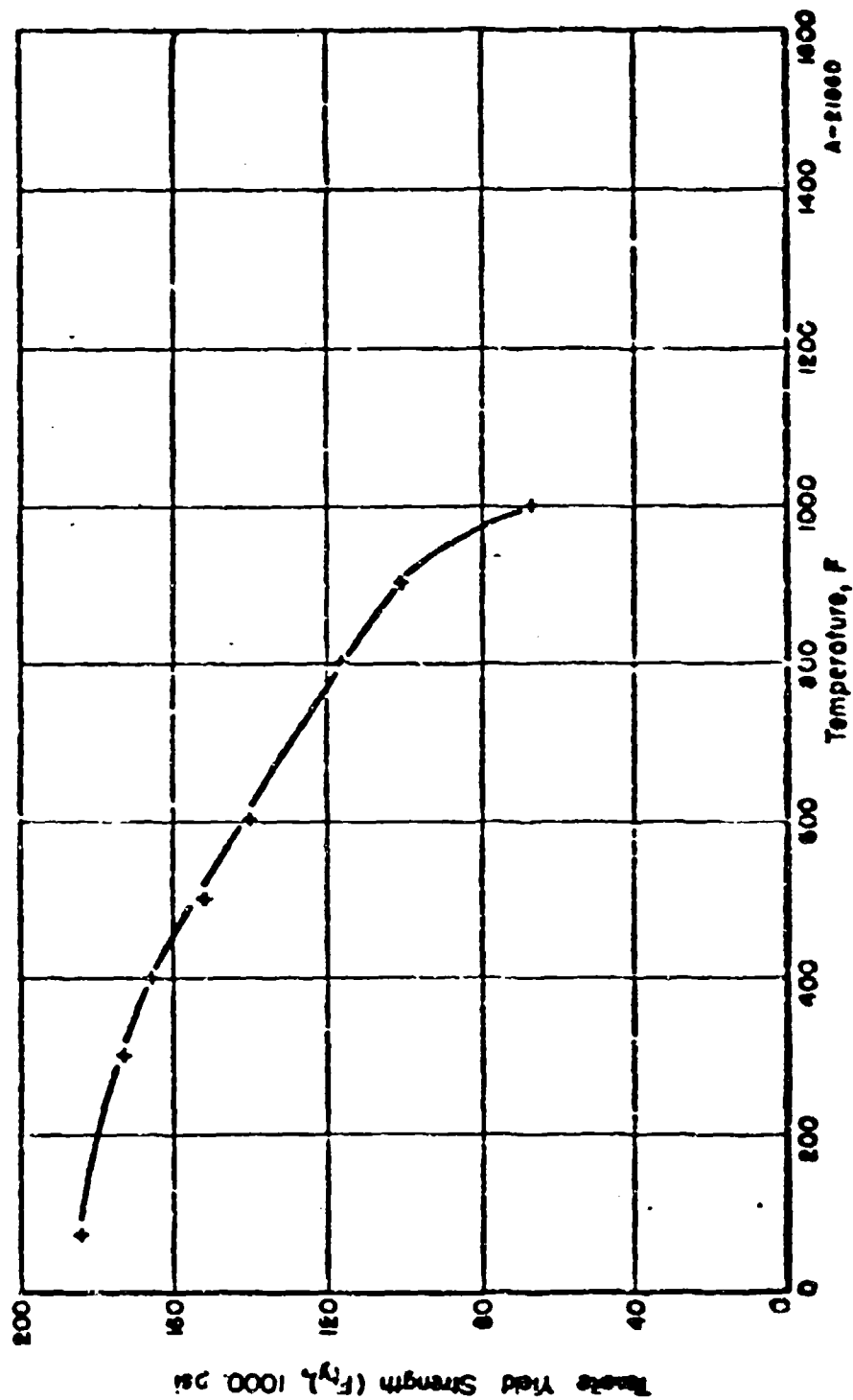


FIGURE 88. TENSILE YIELD STRENGTH (F_y) OF 17-7PH (TH 950) STAINLESS STEEL AT ELEVATED TEMPERATURE

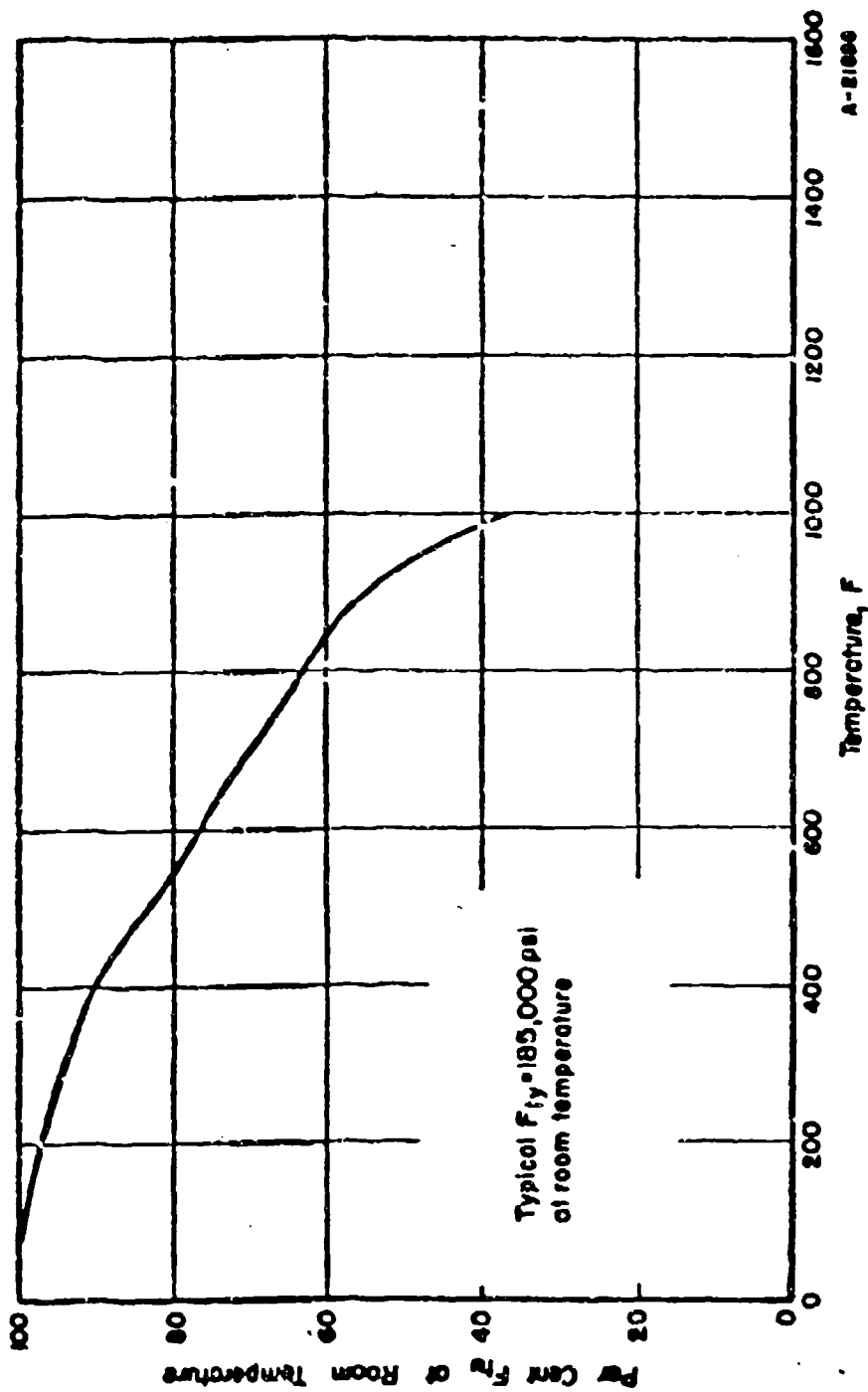


FIGURE 89. DESIGN CURVE FOR TENSILE YIELD STRENGTH (F_{ty}) OF 17-7PH (TH 950) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 215.

AM-350 STAINLESS STEEL

AM-350 is a precipitation-hardenable stainless steel having the nominal composition shown in Table 6.

TABLE 6. NOMINAL CHEMICAL
COMPOSITION OF
AM-350 STAINLESS
STEEL

Element	Weight Per Cent
Carbon	0.08
Manganese	0.50
Silicon	0.40
Chromium	17.00
Nickel	4.20
Molybdenum	2.75
Iron	Balance

As annealed, AM-350 is austenitic and, like other austenitic stainless steels, is soft and ductile in this condition. The composition has been controlled so that the martensite transformation temperature is below 32 F but above -80 F. Hardening is accomplished by "deep freezing" the annealed alloy to -100 F (i.e., below the M_s temperature, which allows the austenite-martensite transformation to proceed), followed by tempering the martensitic structure at about 750 F. It is pointed out that at 750 F no precipitation occurs but that the desired strength properties are obtained from the tempering of the martensite. A double-aging treatment is a second heat-treating method.

Annealing temperature has a noticeable effect on the properties obtained after aging; 1750 F is the optimum annealing temperature for the "deep-freeze and temper" treatment, while 1950 F is preferred for the "double-age" heat treatment.

The short-time, elevated-temperature properties of AM-350 are shown in the following curves:

- (1) Tensile properties, Figures 90 through 93, 95 through 98, and 100 through 103.
- (2) Modulus of elasticity, Figures 94, 99, 104, 109, and 112.
- (3) Shear properties, Figures 105 and 106.

(4) Compressive properties, Figures 107 and 108

(5) Stress-strain curves, Figures 110, 111, and 113 through 125.

Data on all strength properties except bearing strength are available on AM-350.

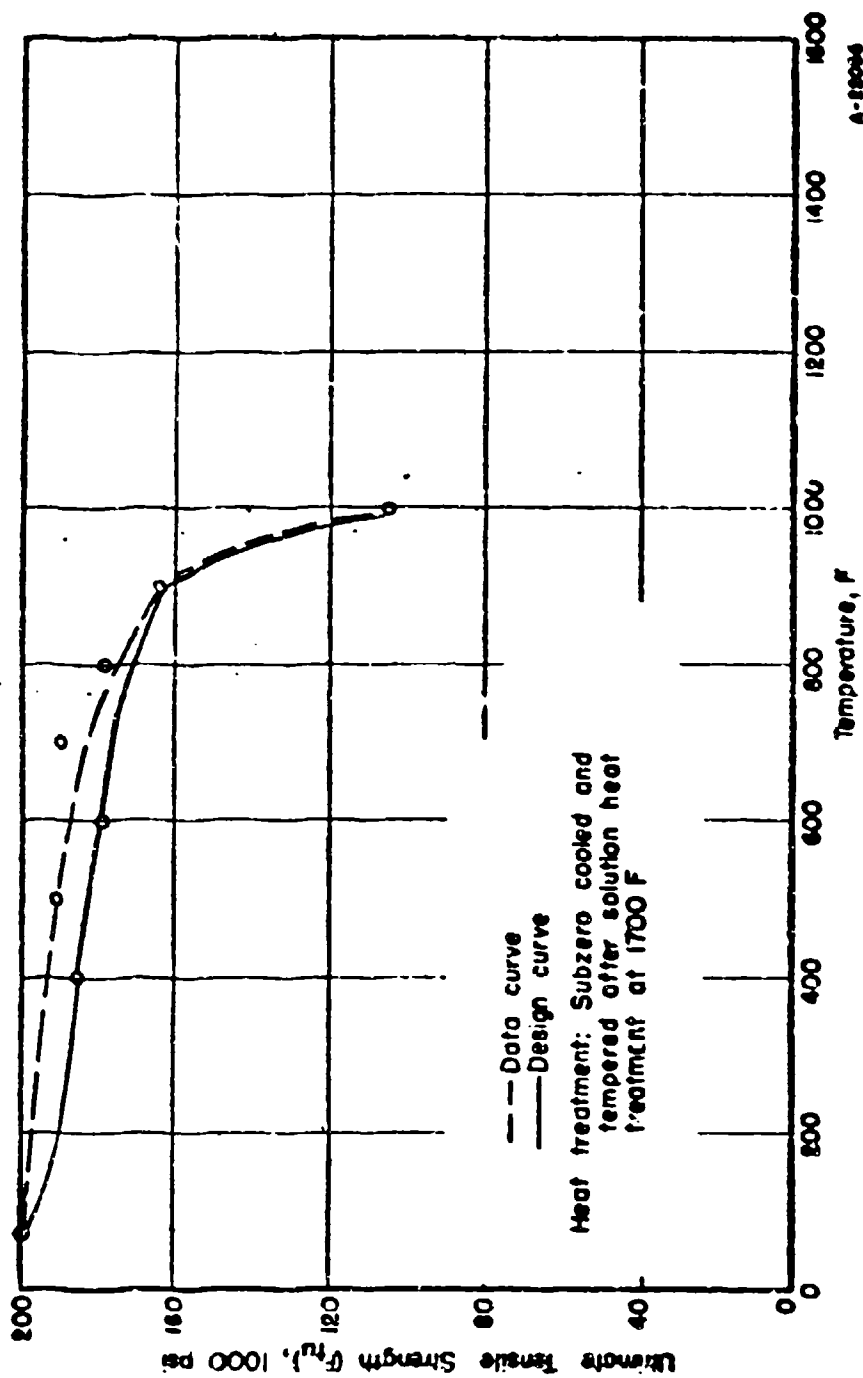


FIGURE 90. TENSILE STRENGTH (F_{tu}) OF AM-350 STAINLESS STEEL (SOLUTION HEAT TREATED AT 1700 F) AT ELEVATED TEMPERATURE

Ref. 358.

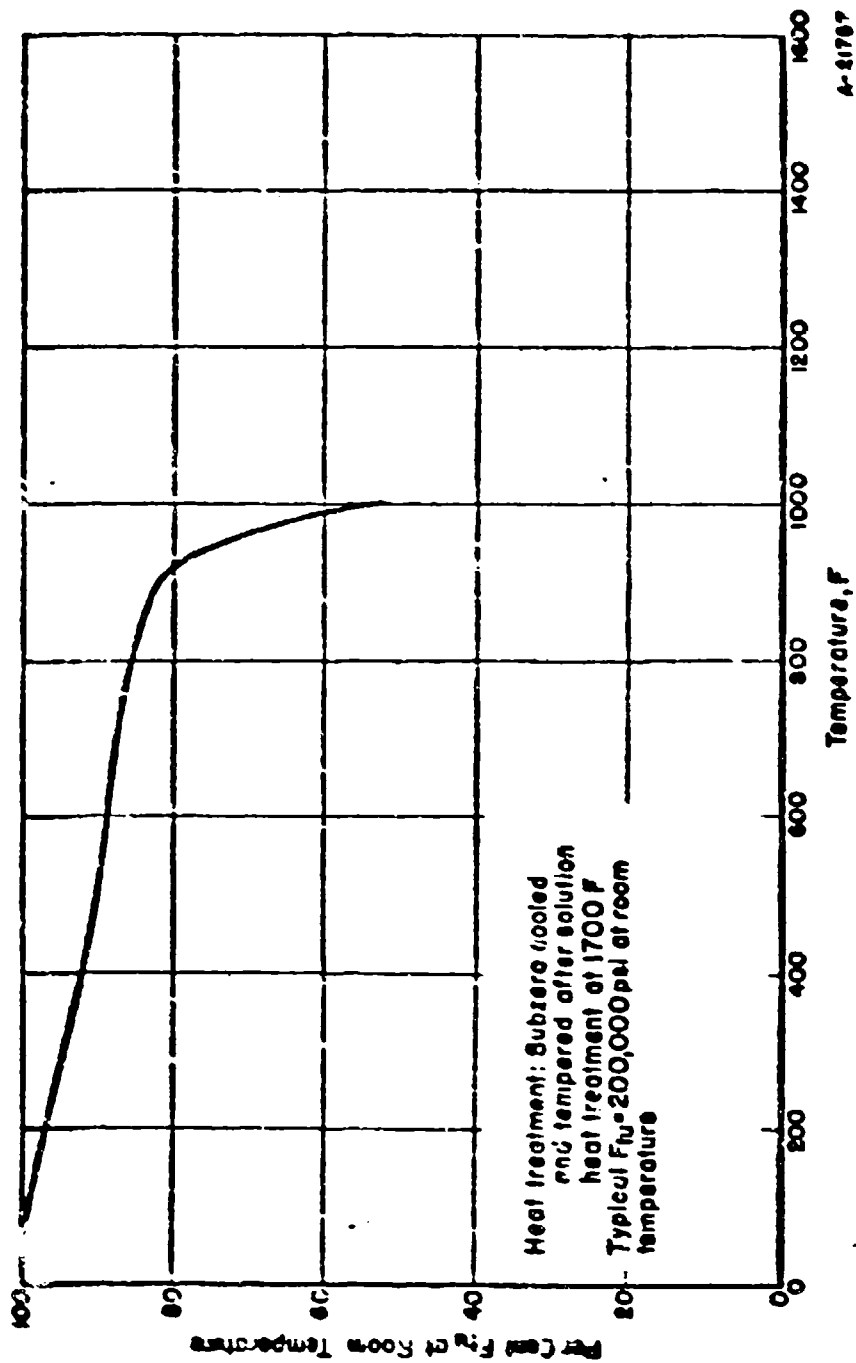


FIGURE 91. DESIGN CURVE FOR TENSILE STRENGTH (F_t) OF AM-350 STAINLESS STEEL
(SOLUTION HEAT TREATED AT 1700 F) AT ELEVATED TEMPERATURE

Ref. 358.

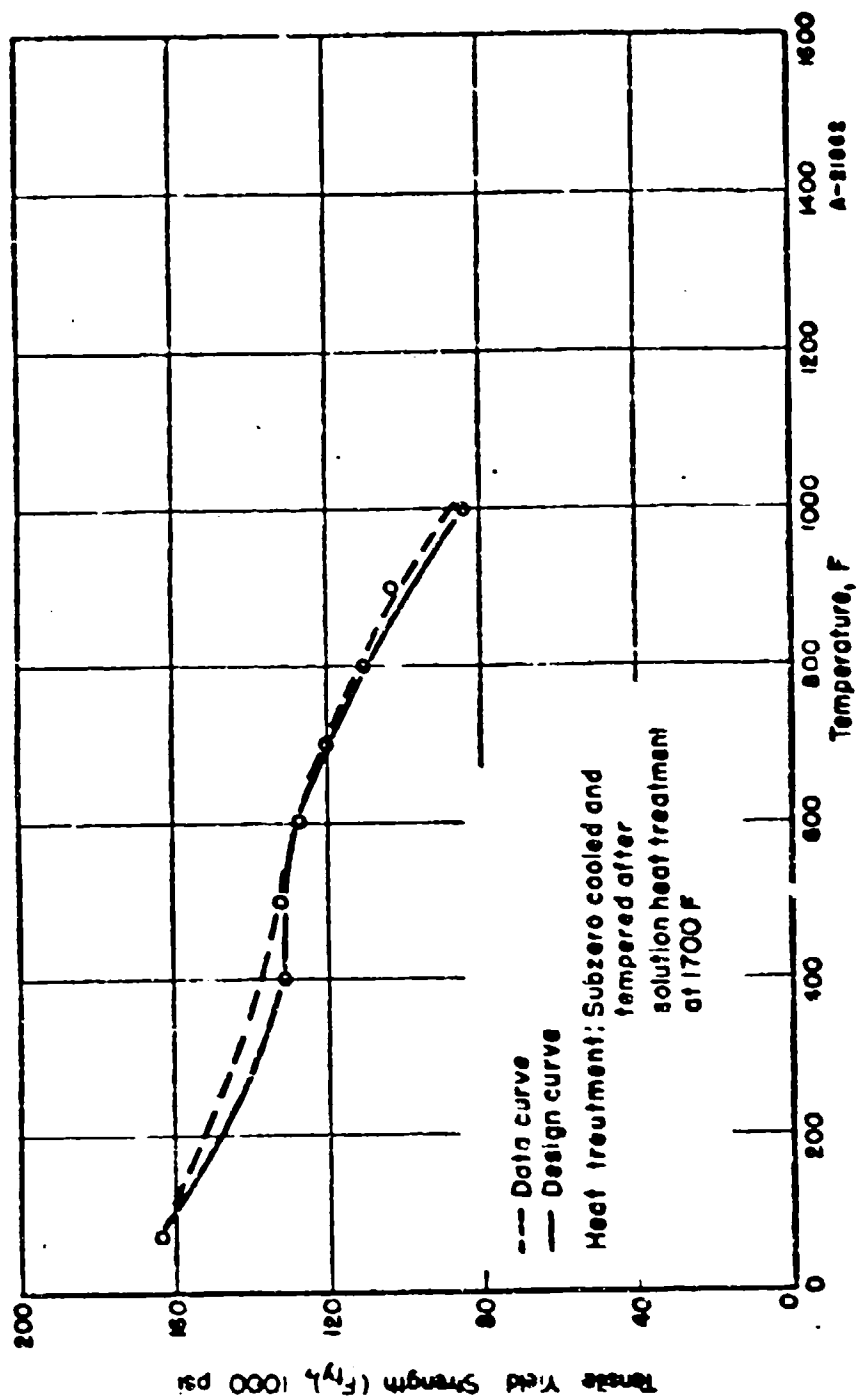


FIGURE 92. TENSILE YIELD STRENGTH (F_y) OF AM-150 STAINLESS STEEL (SOLUTION HEAT TREATED AT 1700 F) AT ELEVATED TEMPERATURE

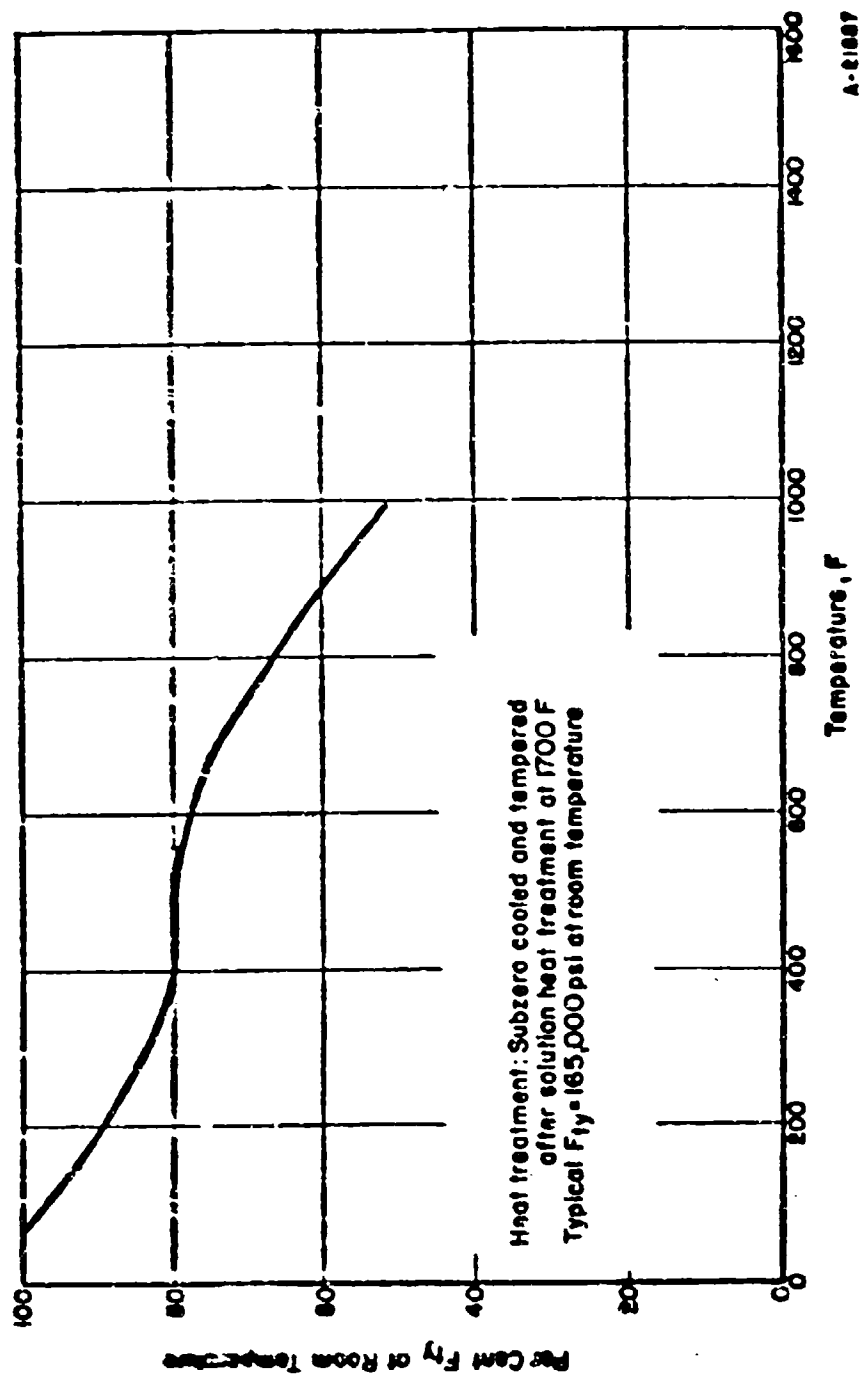


FIGURE 93. DESIGN CURVE FOR TENSILE YIELD STRENGTH (F_{ty}) OF AM-350 STAINLESS STEEL (SOLUTION HEAT TREATED AT 1700 F) AT ELEVATED TEMPERATURE

Ref. 358.

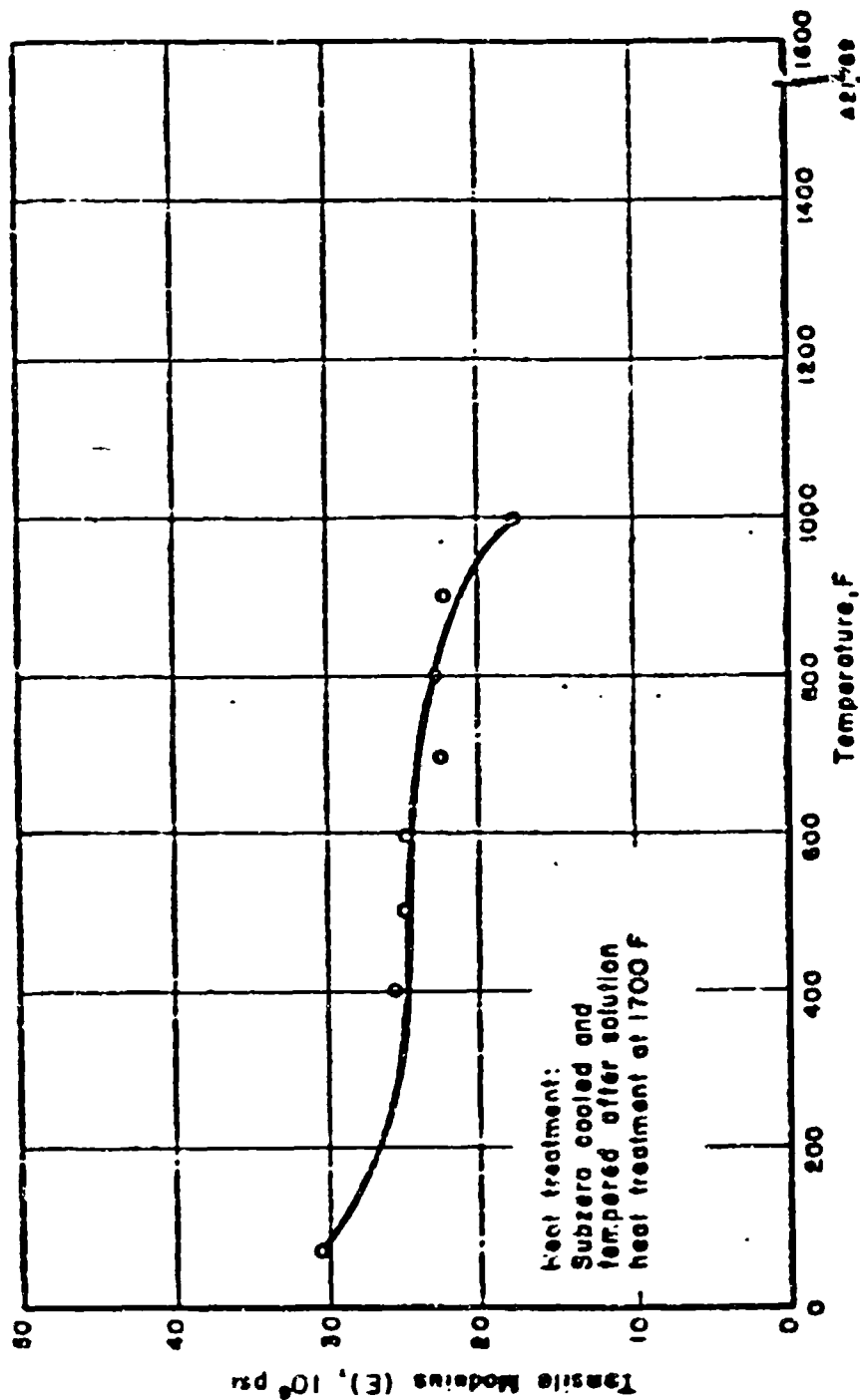


FIGURE 94. TENSILE MODULUS (E) OF AM-350 STAINLESS STEEL (SOLUTION HEAT TREATED AT 1700 F) AT ELEVATED TEMPERATURE
Ref. 358.

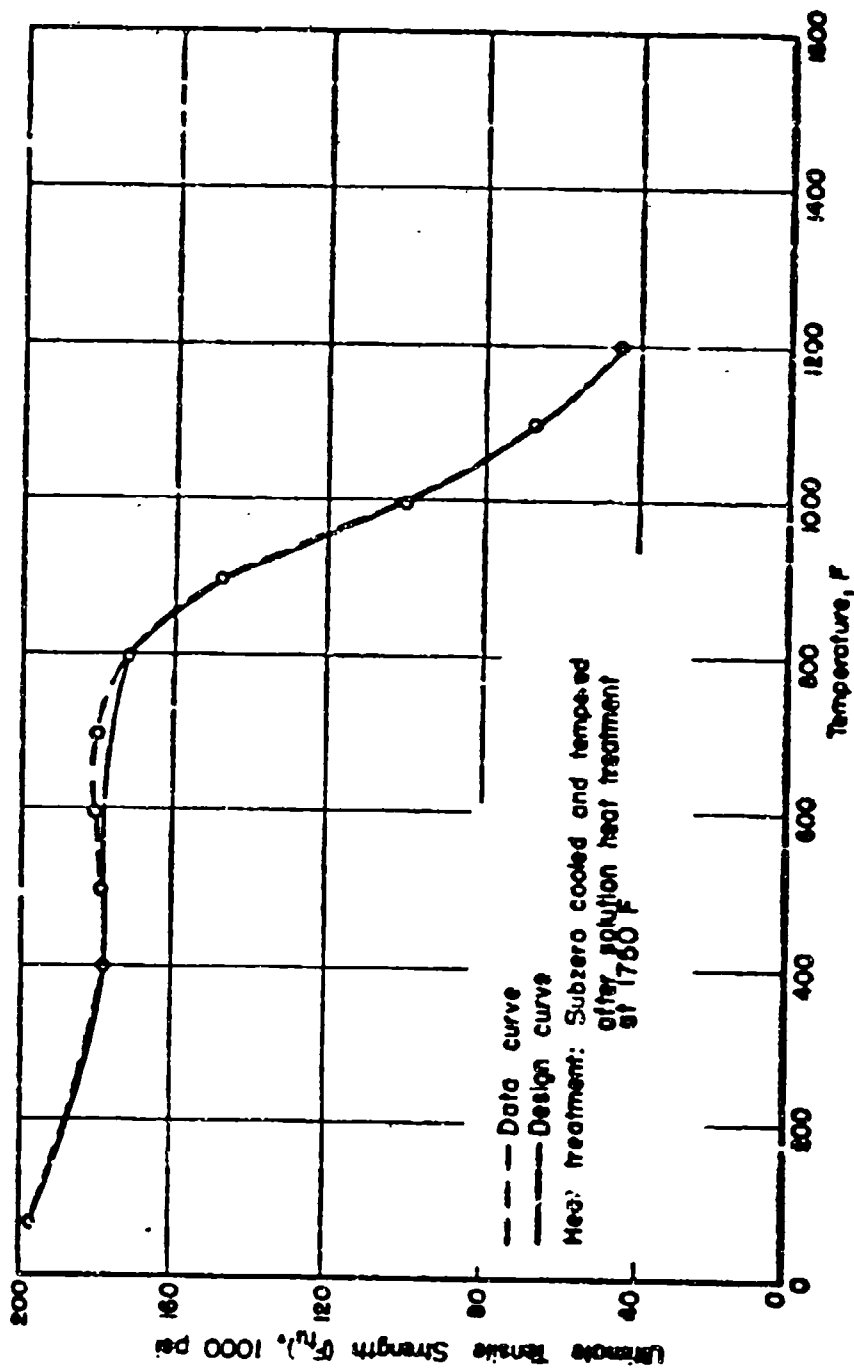


FIGURE 95. TENSILE STRENGTH (F_{tu}) OF AM-350 STAINLESS STEEL (SOLUTION HEAT TREATED AT 1750 F) AT ELEVATED TEMPERATURE

Ref. 358.

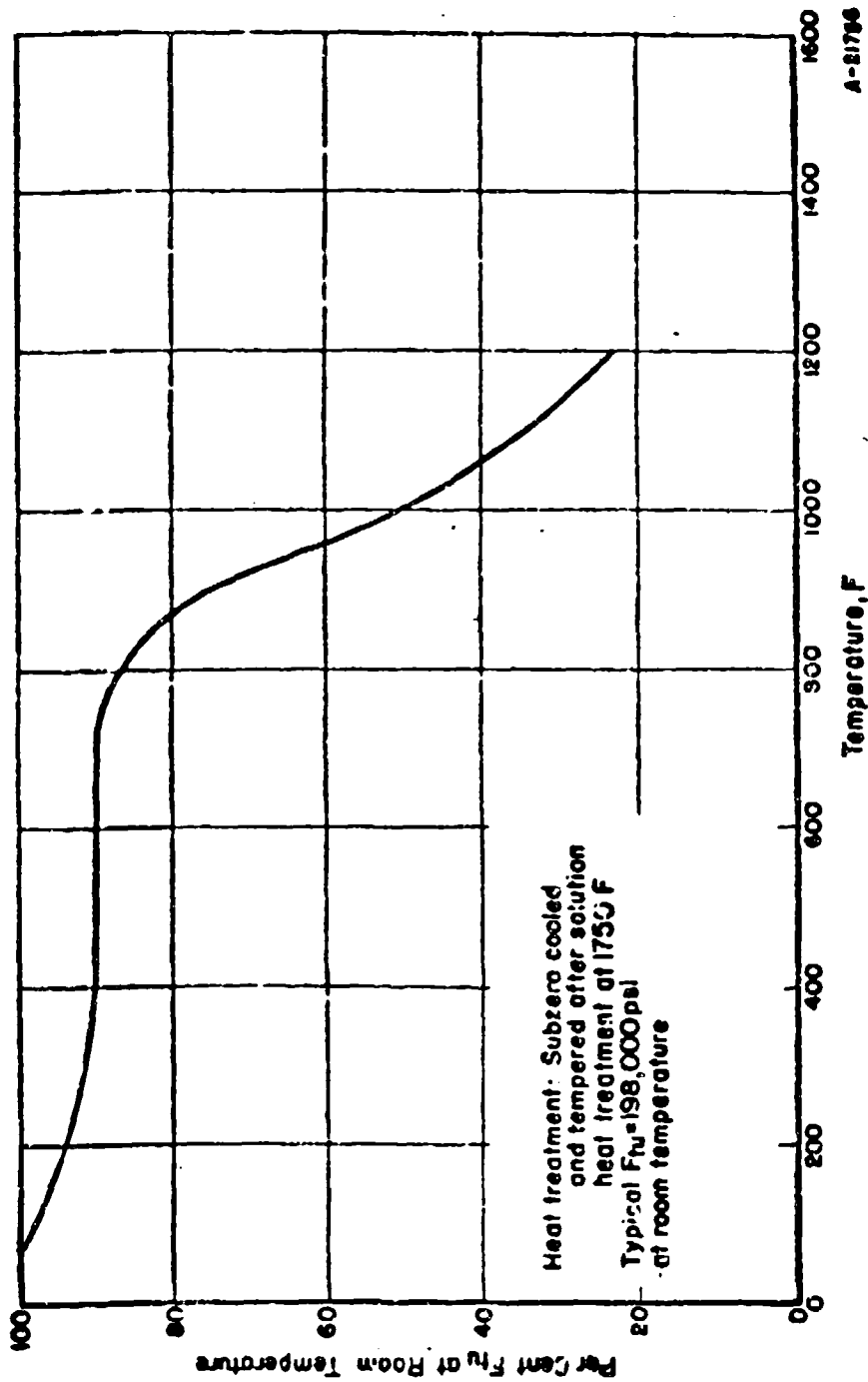


FIGURE 96. DESIGN CURVE FOR TENSILE STRENGTH (F_m) OF AM-350 STAINLESS STEEL (SOLUTION HEAT TREATED AT 1750 F) AT ELEVATED TEMPERATURE

Ref. 358.

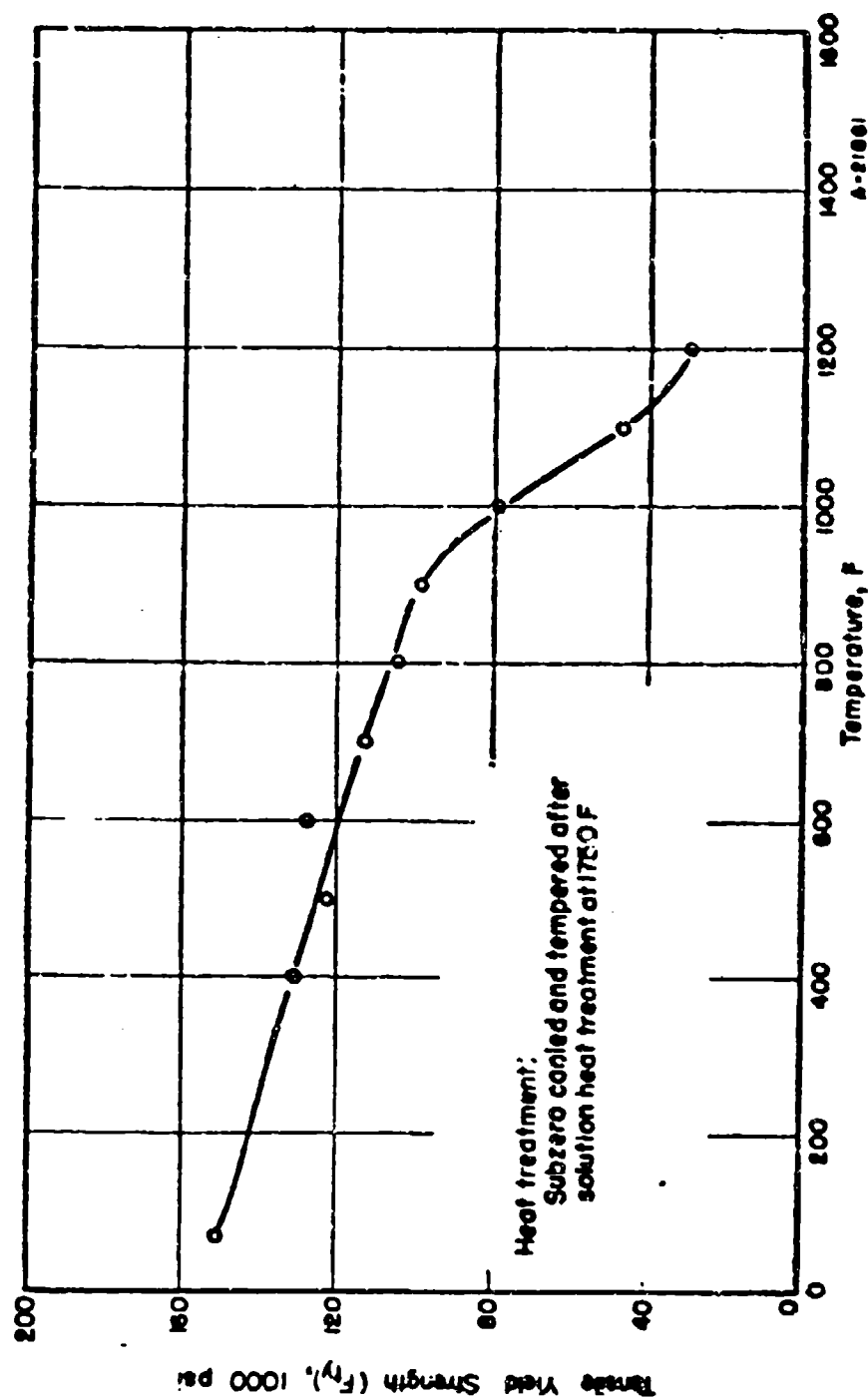


FIGURE 97. TENSILE YIELD STRENGTH (F_y) OF AM-350 STAINLESS STEEL, (SOLUTION HEAT TREATED AT 1750 F) AT ELEVATED TEMPERATURE

Ref. 356.

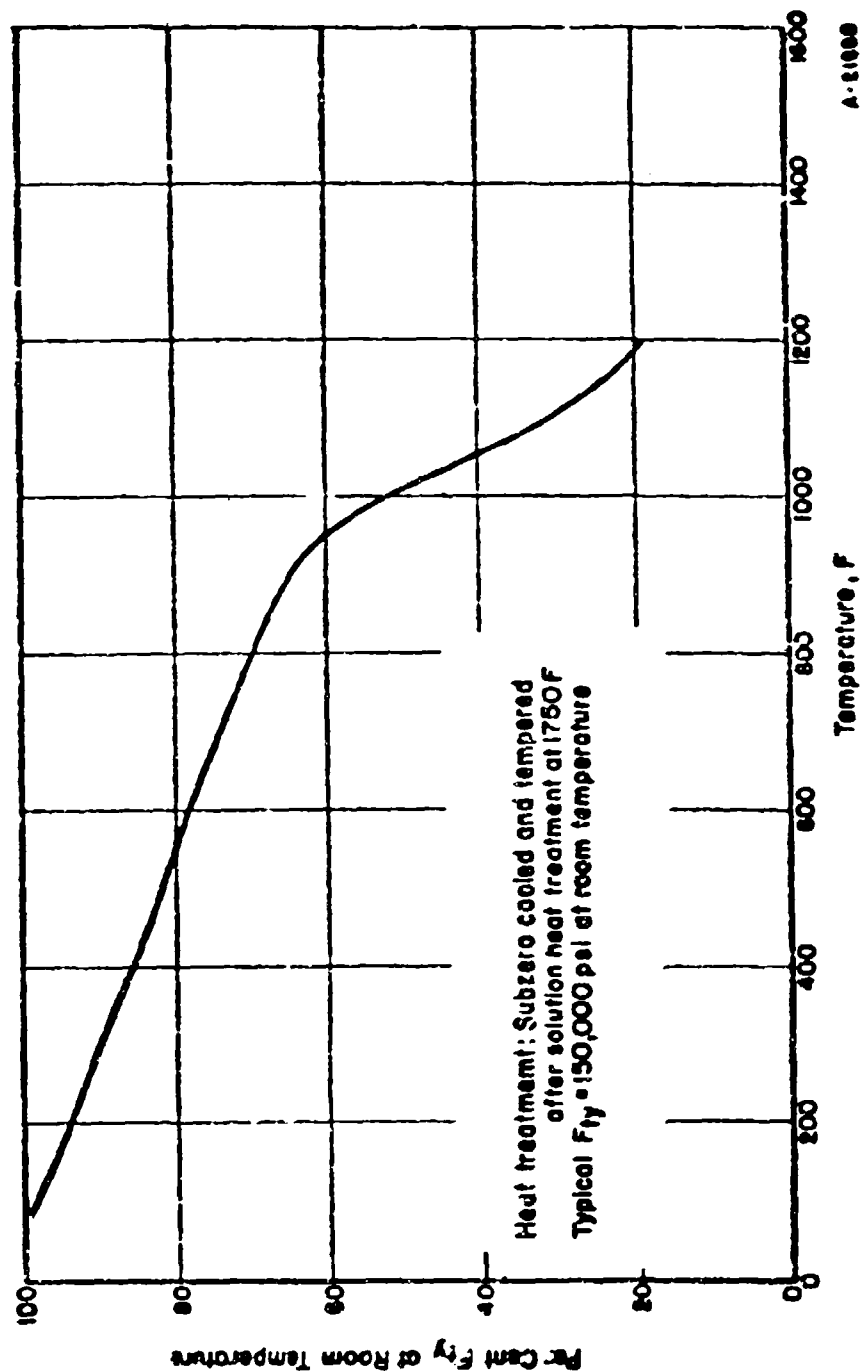


FIGURE 98. DESIGN CURVE FOR TENSILE YIELD STRENGTH (F_T) OF AM-350 STAINLESS STEEL (SOLUTION HEAT TREATED AT 1750 F) AT ELEVATED TEMPERATURE

Ref. 35f.

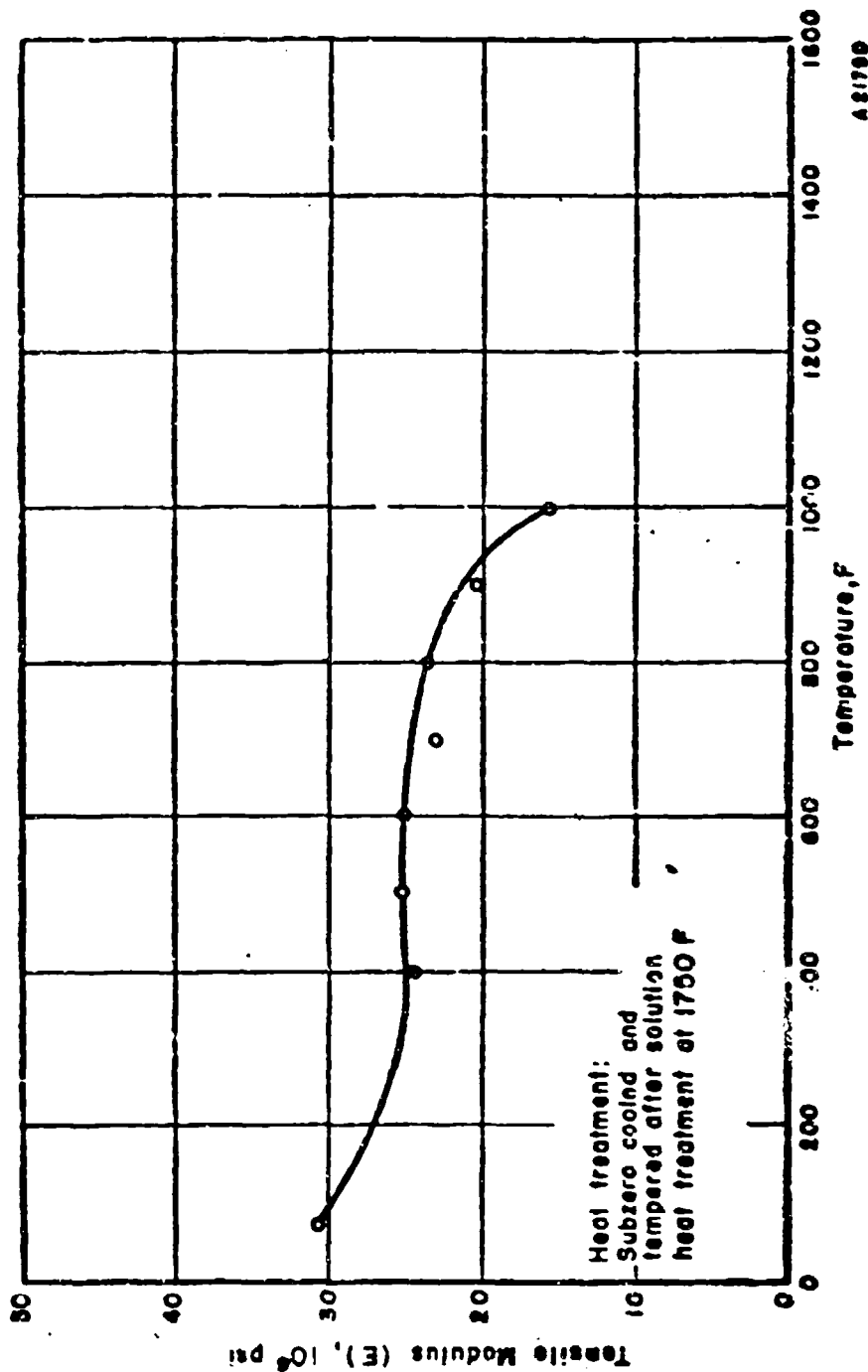


FIGURE 99. TENSILE MODULUS (E) OF AM-350 STAINLESS STEEL (SOLUTION HEAT TREATED AT 1750 F) AT ELEVATED TEMPERATURE

Ref. 398.

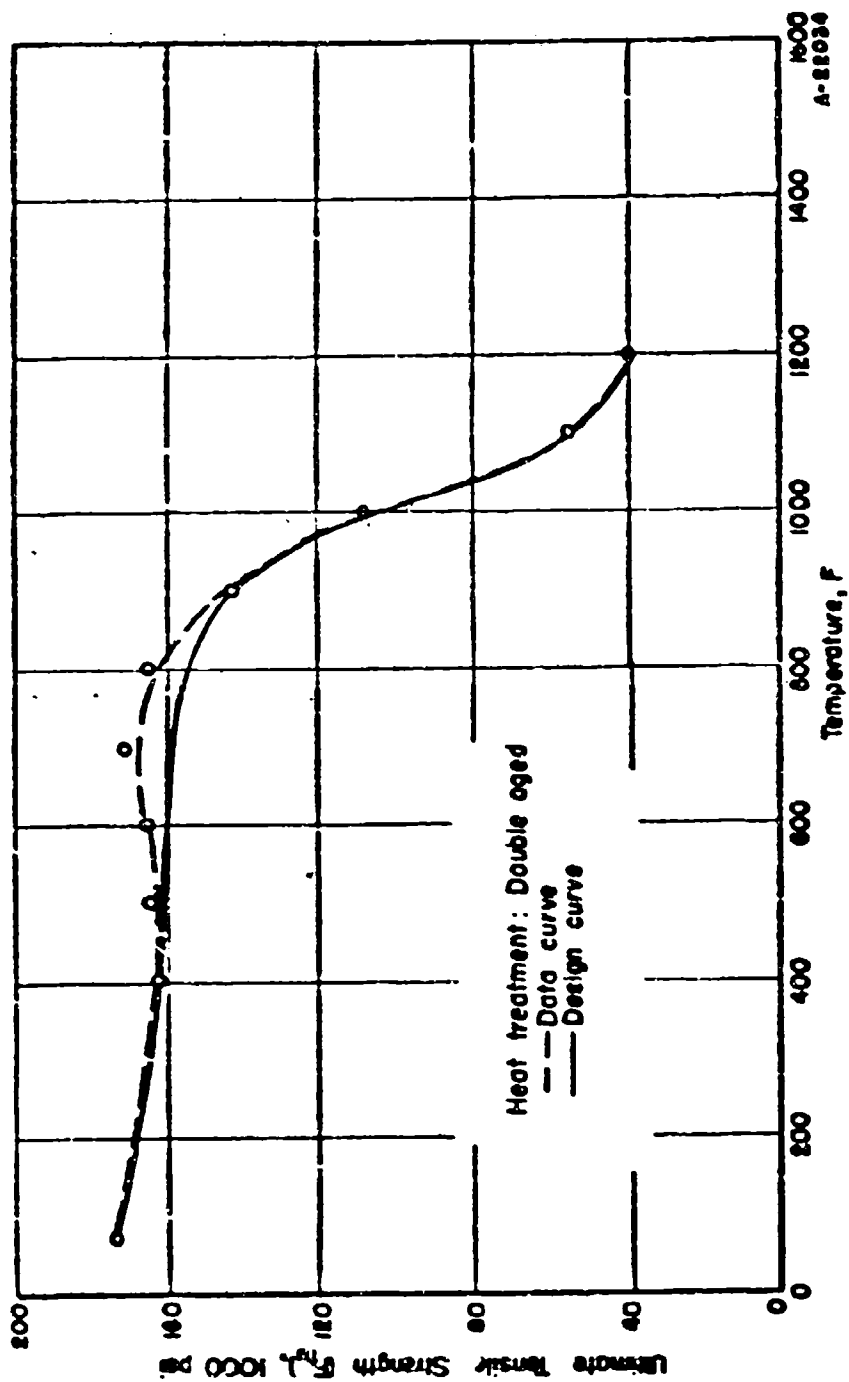


FIGURE 100. TENSILE STRENGTH (F_{tu}) OF AM-350 STAINLESS STEEL (DOUBLE AGED) AT ELEVATED TEMPERATURE

Ref. 358.

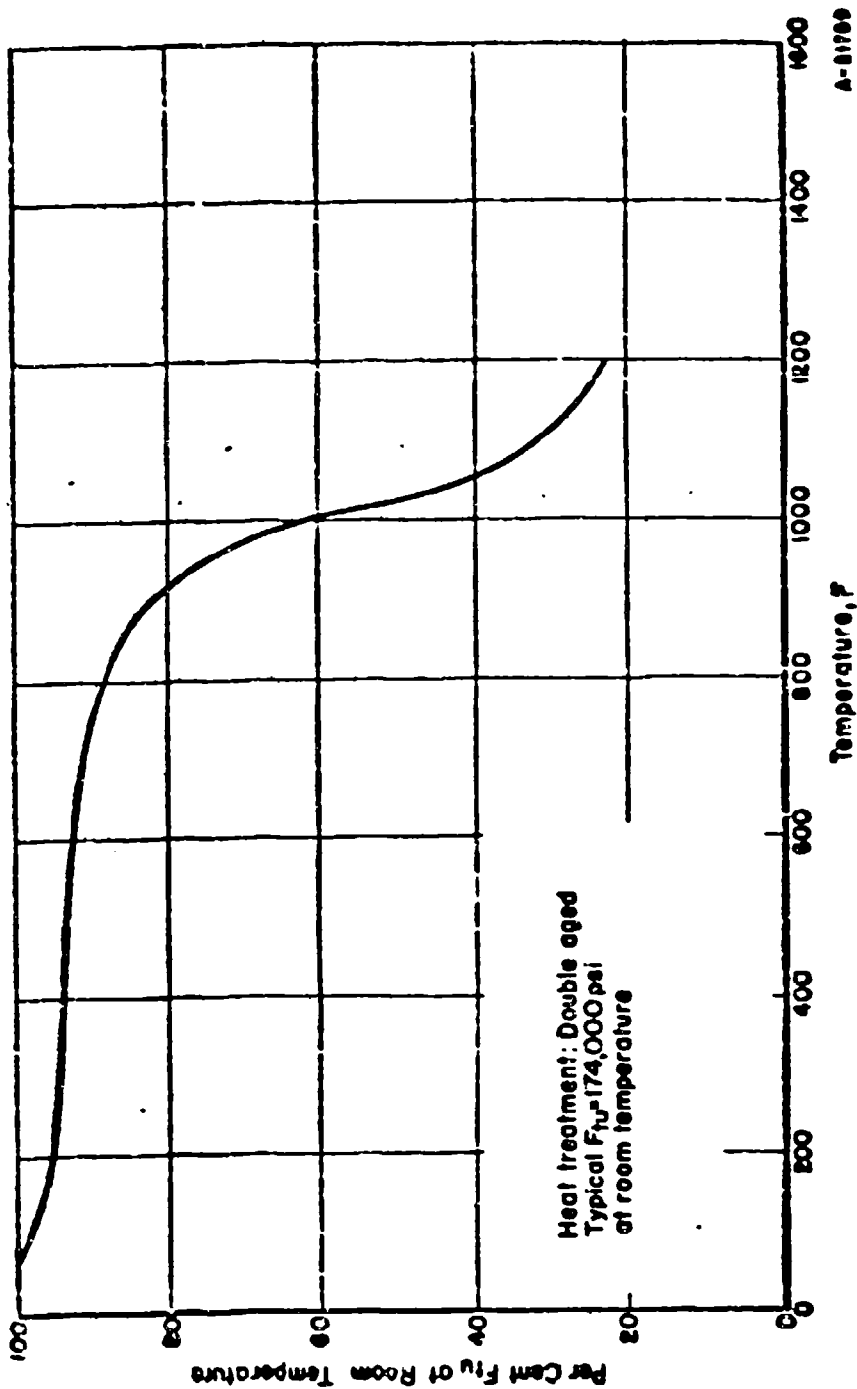


FIGURE 101. DESIGN CURVE FOR TENSILE STRENGTH (F_u) OF AM-350 STAINLESS STEEL (DOUBLE AGED) AT ELEVATED TEMPERATURE

Ref. 388.

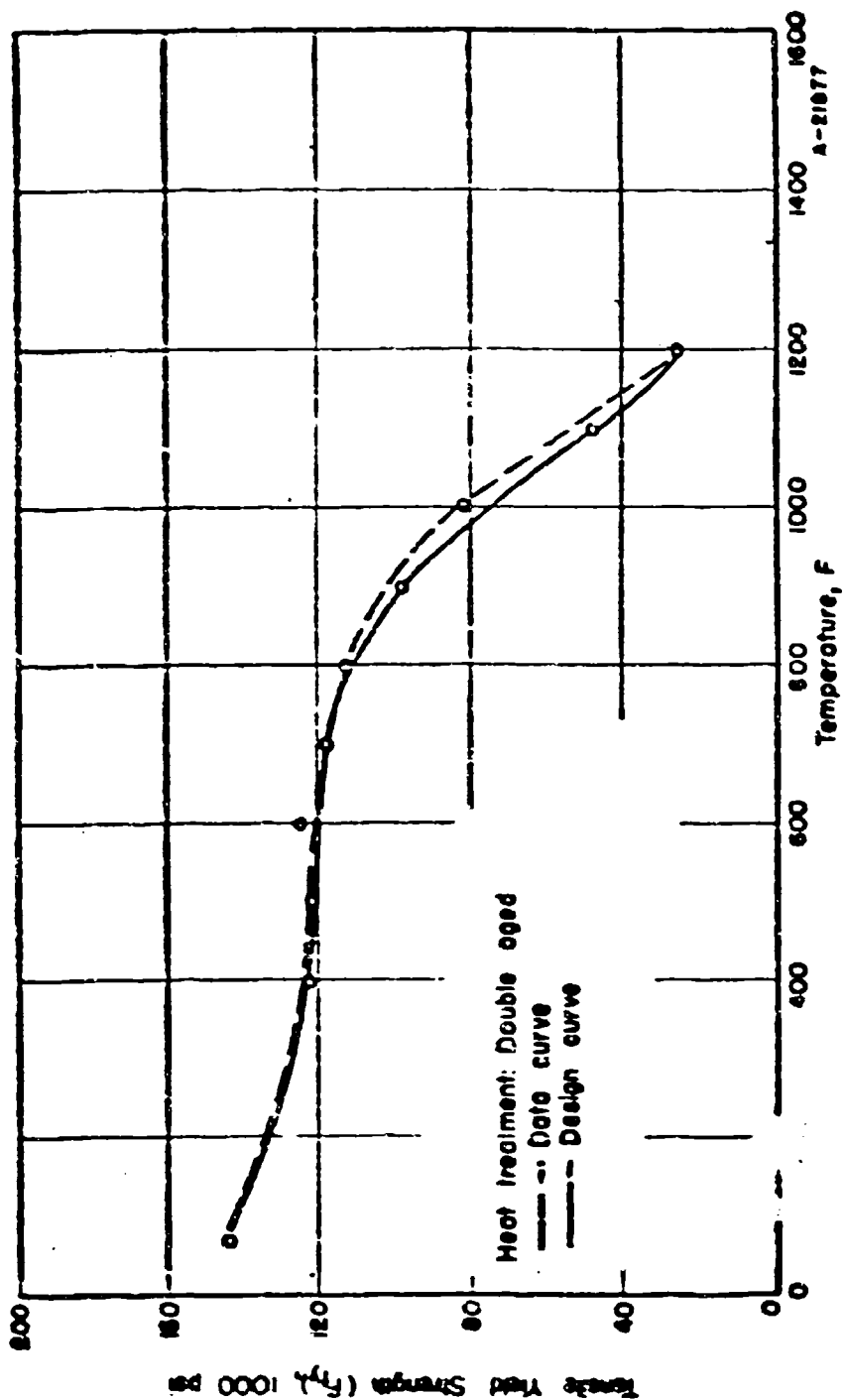


FIGURE 102. TENSILE YIELD STRENGTH (F_y) OF AM-350 STAINLESS STEEL (DOUBLE AGED) AT ELEVATED TEMPERATURE

Ref. 358.

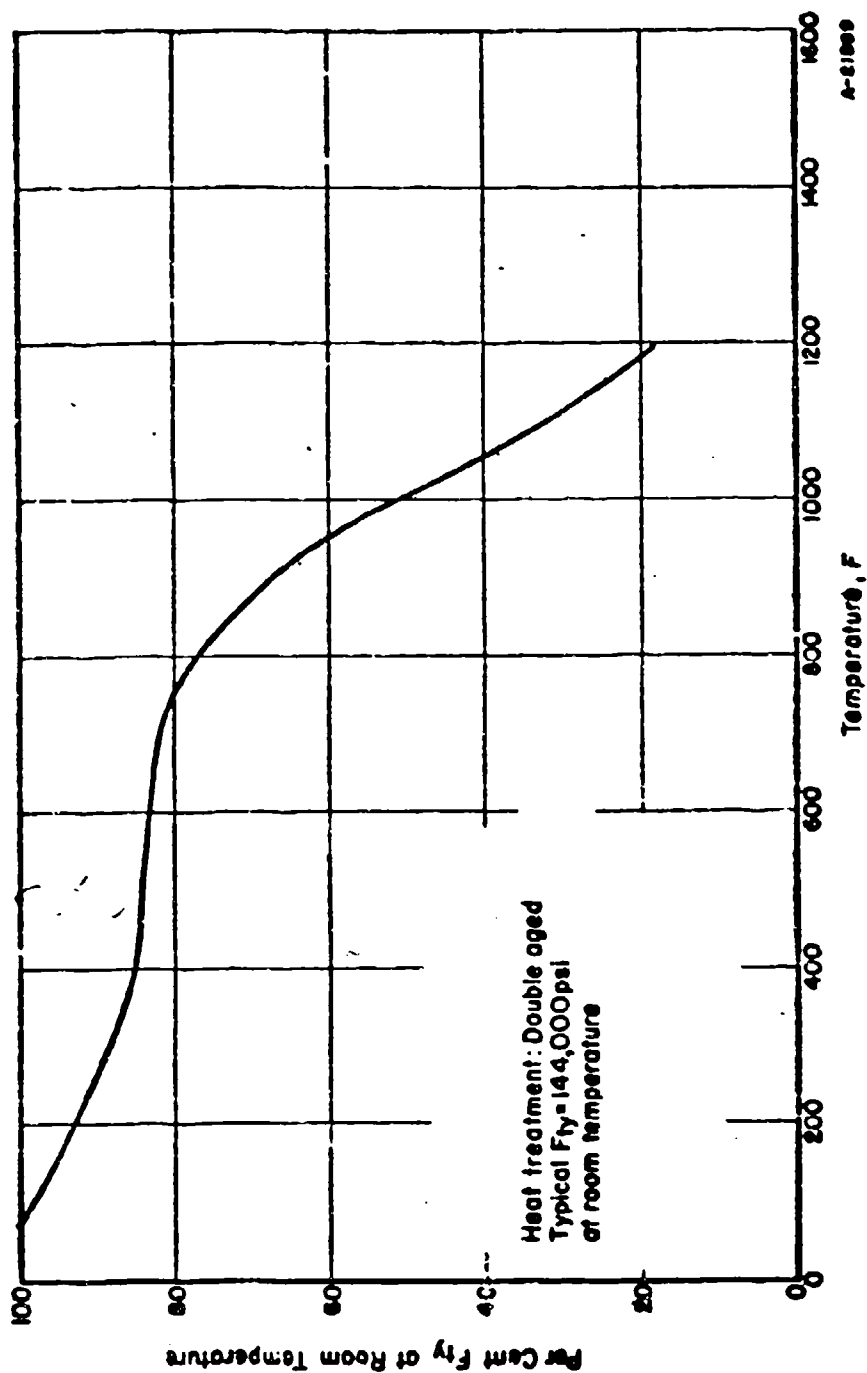


FIGURE 101. DESIGN CURVE FOR TENSILE YIELD STRENGTH (F_{ty}) OF AM-350 STAINLESS STEEL (DOUBLE AGED) AT ELEVATED TEMPERATURE
Ref. 358.

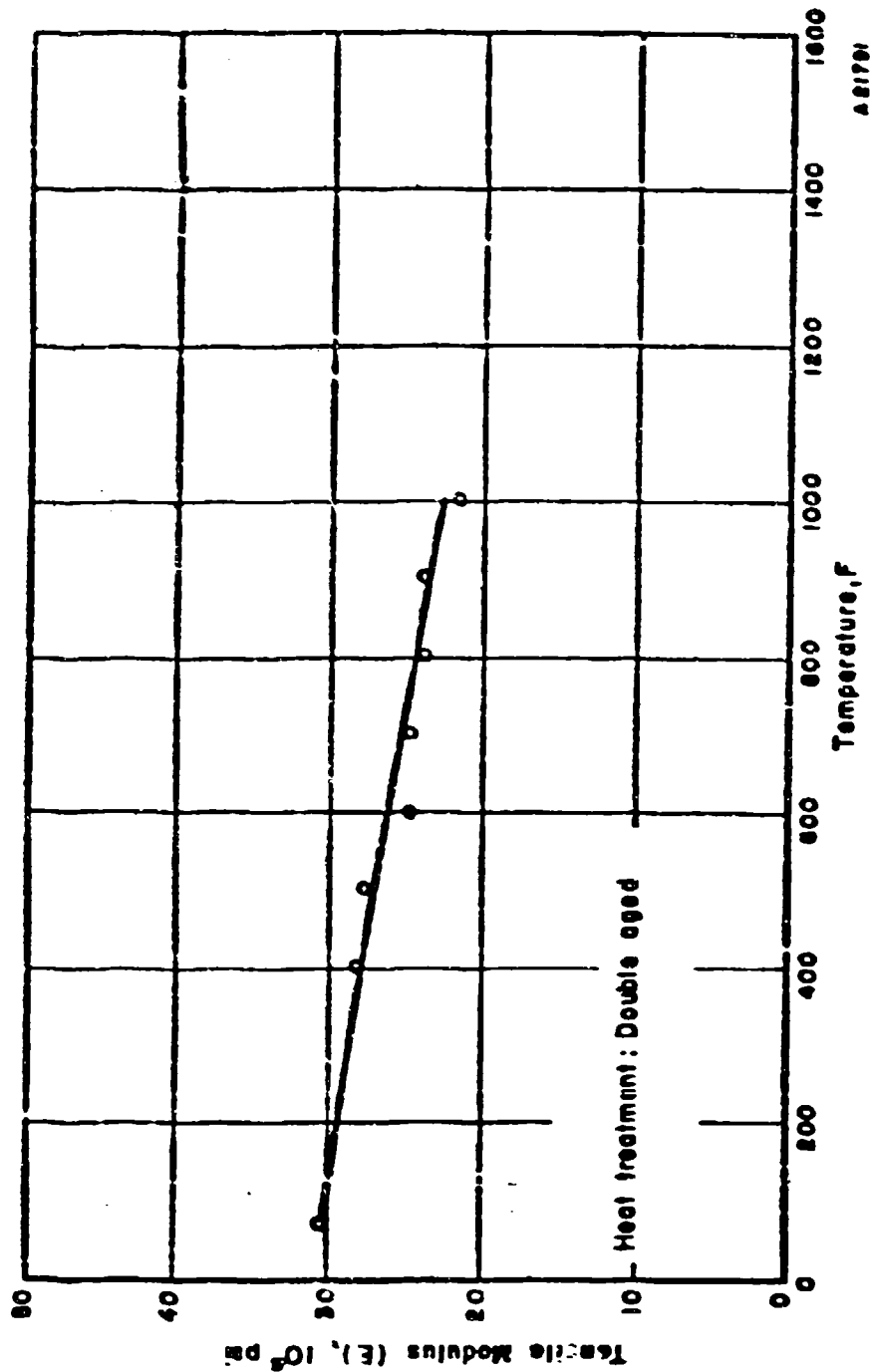


FIGURE 104. TENSILE MODULUS (E) OF AM-350 STAINLESS STEEL (DOUBLED AGED) AT ELEVATED TEMPERATURE

Ref. 358.

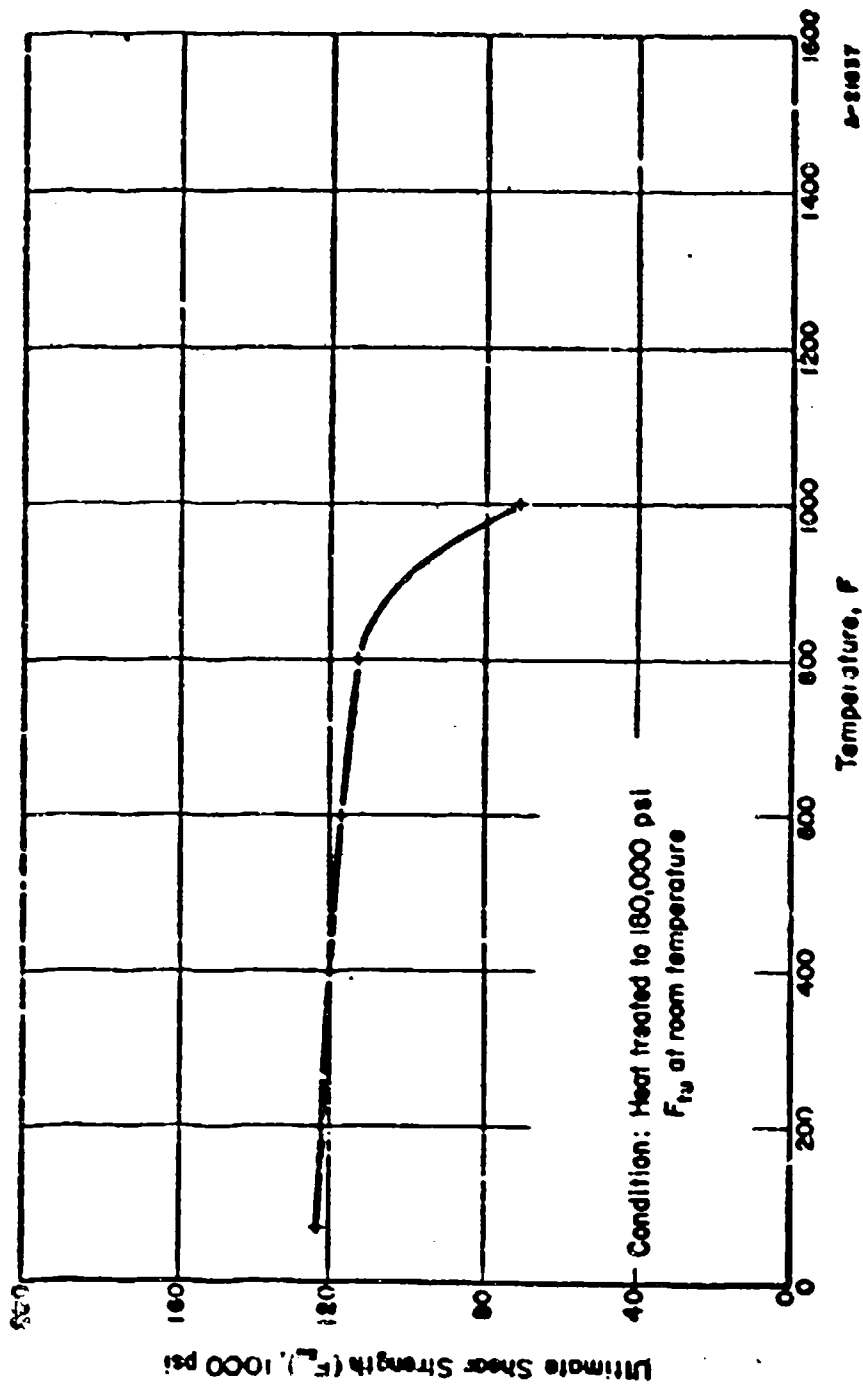


FIGURE 105, SHEAR STRENGTH (F_{su}) OF AM-350 STAINLESS STEEL AT ELEVATED TEMPERATURE

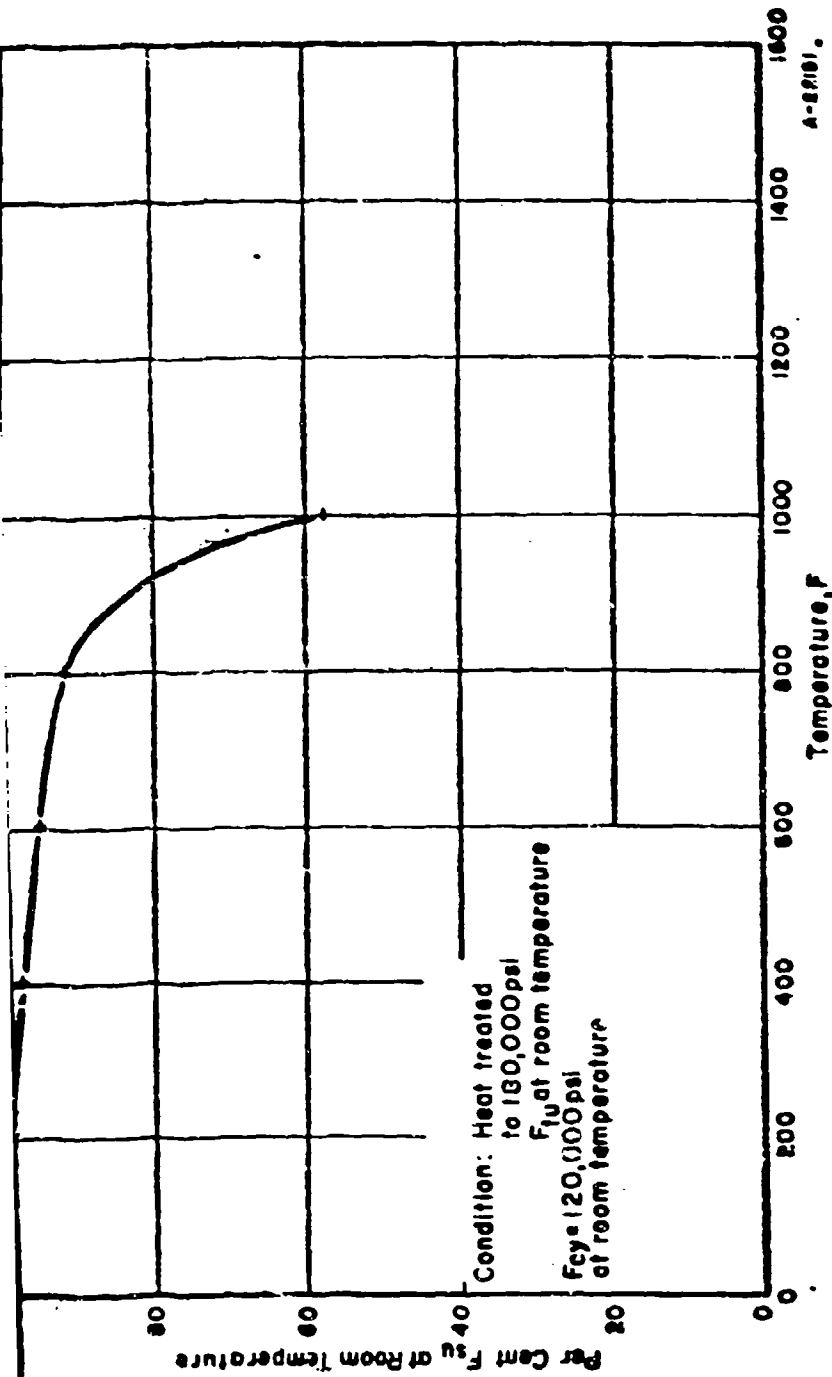


FIGURE 106. DESIGN CURVE FOR SHEAR STRENGTH (F_{su}) OF AM-350 STAINLESS STEEL AT ELEVATED TEMPERATURE

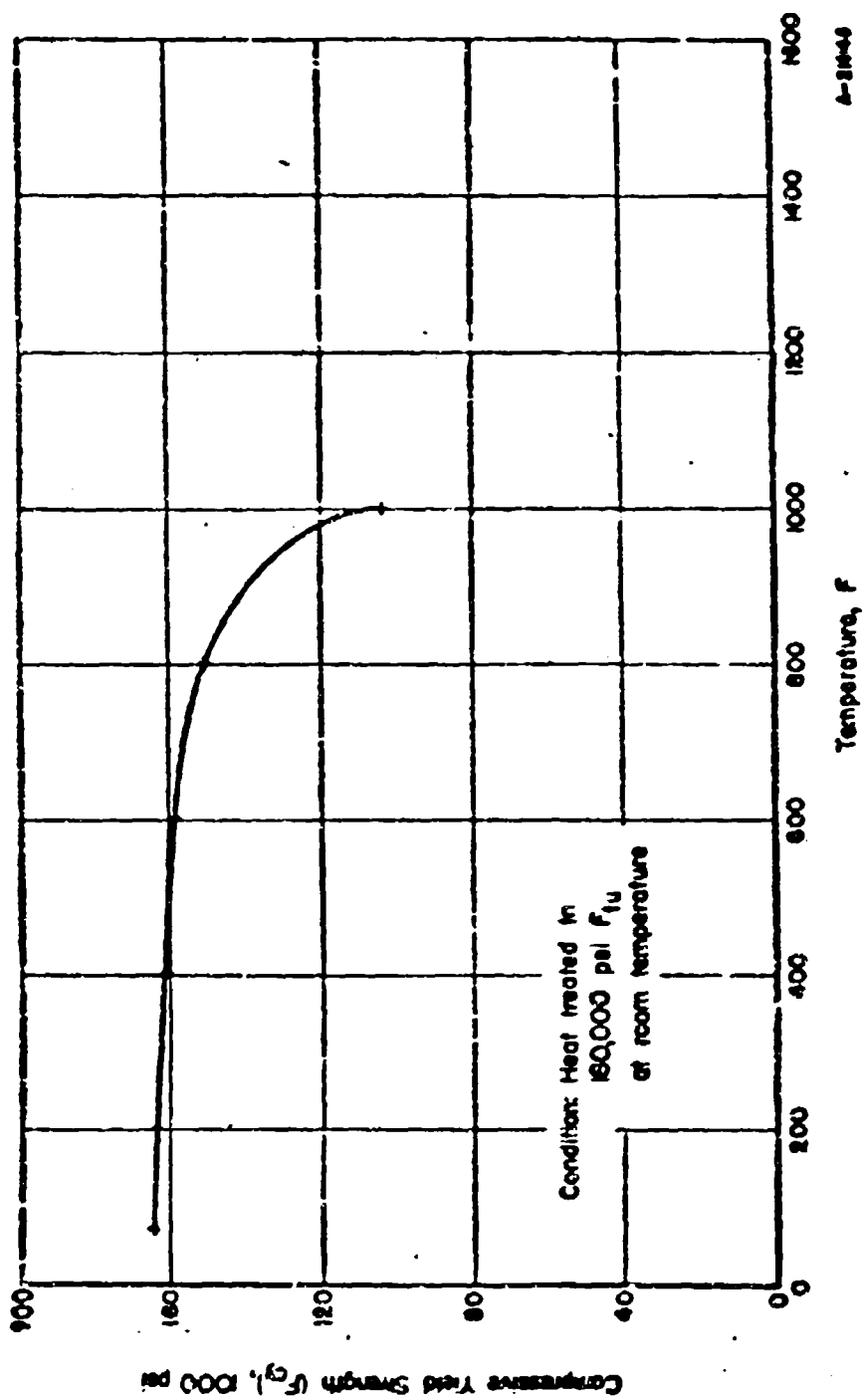


FIGURE 107. COMPRESSIVE YIELD STRENGTH (F_{cy}) OF AM-350 STAINLESS STEEL AT ELEVATED TEMPERATURE

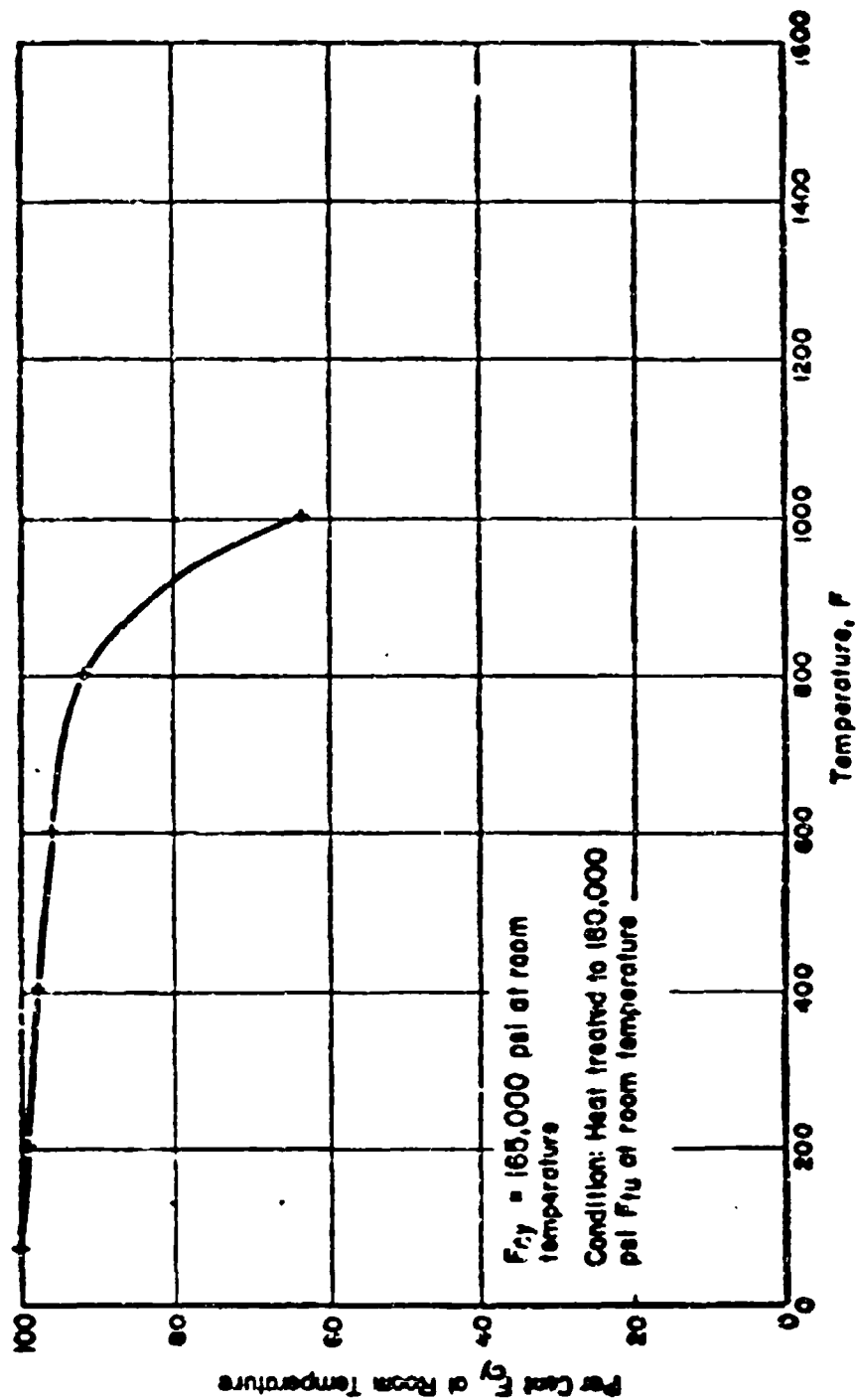


FIGURE 108. DESIGN CURVE FOR COMPRESSIVE YIELD STRENGTH (F_{cy}) OF AM-350 STAINLESS STEEL AT ELEVATED TEMPERATURE

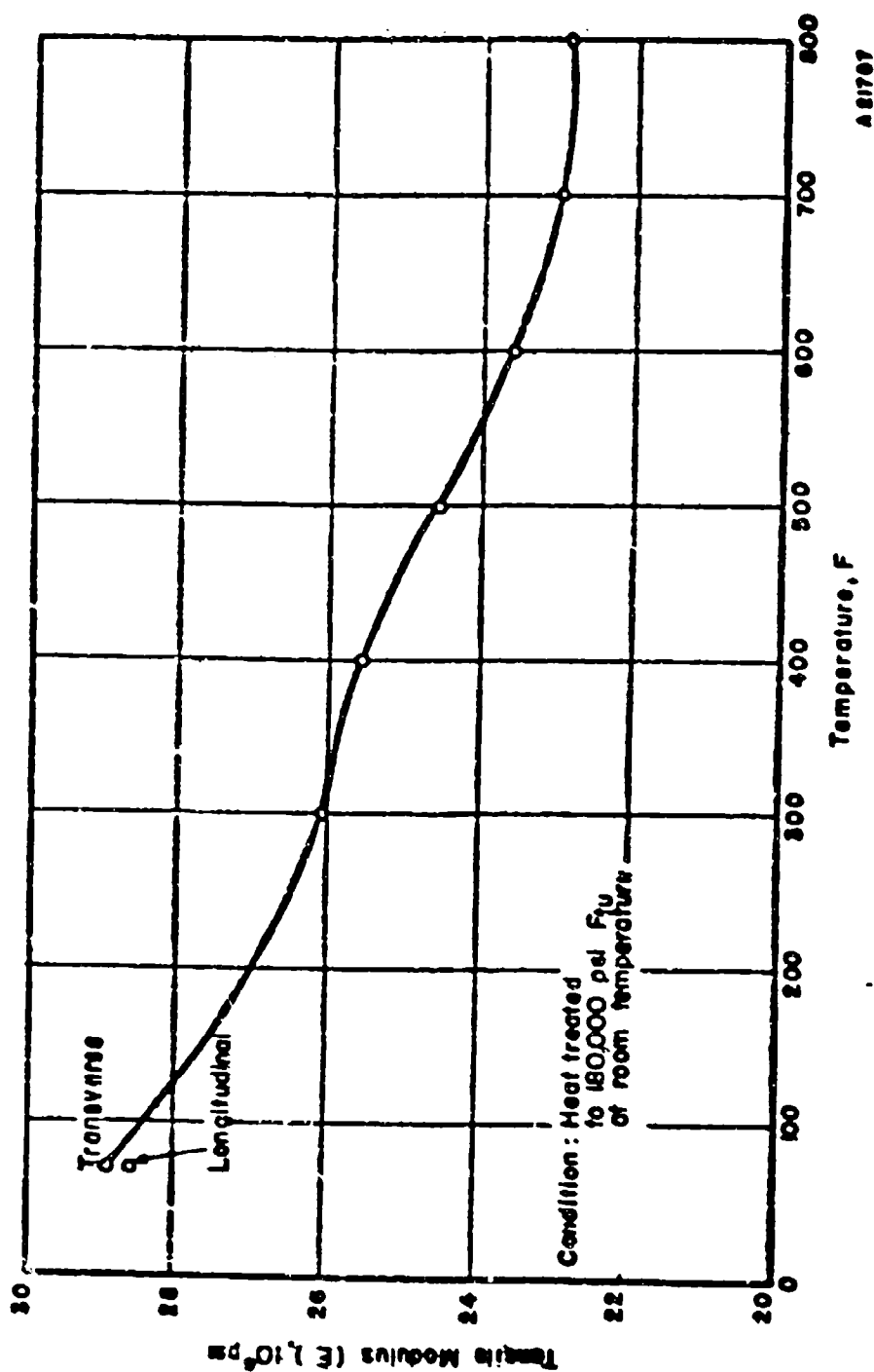


FIGURE 109. TENSILE MODULUS (E) OF AM-350 STAINLESS STEEL AT ELEVATED TEMPERATURE

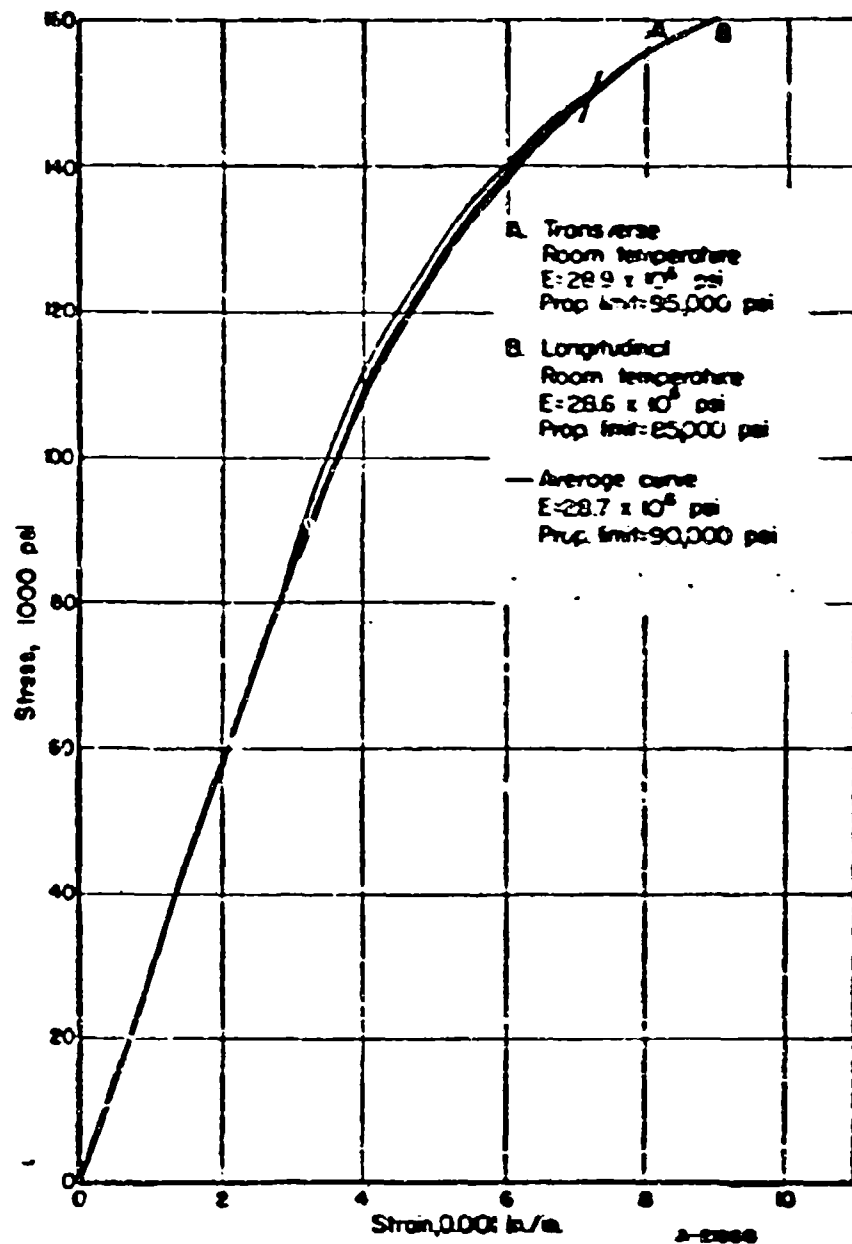


FIGURE 110. TENSILE STRESS-STRAIN CURVES FOR AM-350 STAINLESS STEEL AT ROOM TEMPERATURE

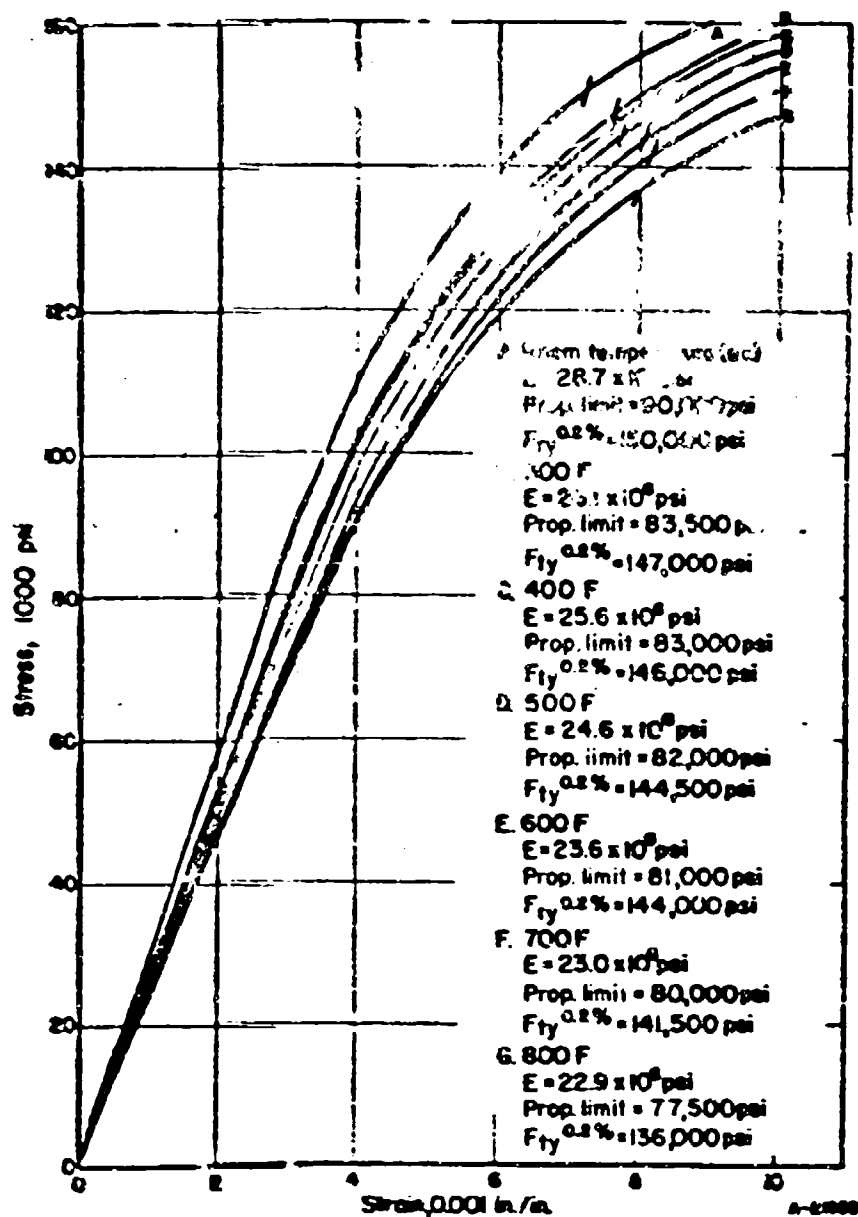


FIGURE 111. TENSILE STRESS-STRAIN CURVES FOR AM-350 STAINLESS STEEL AT ROOM AND ELEVATED TEMPERATURE

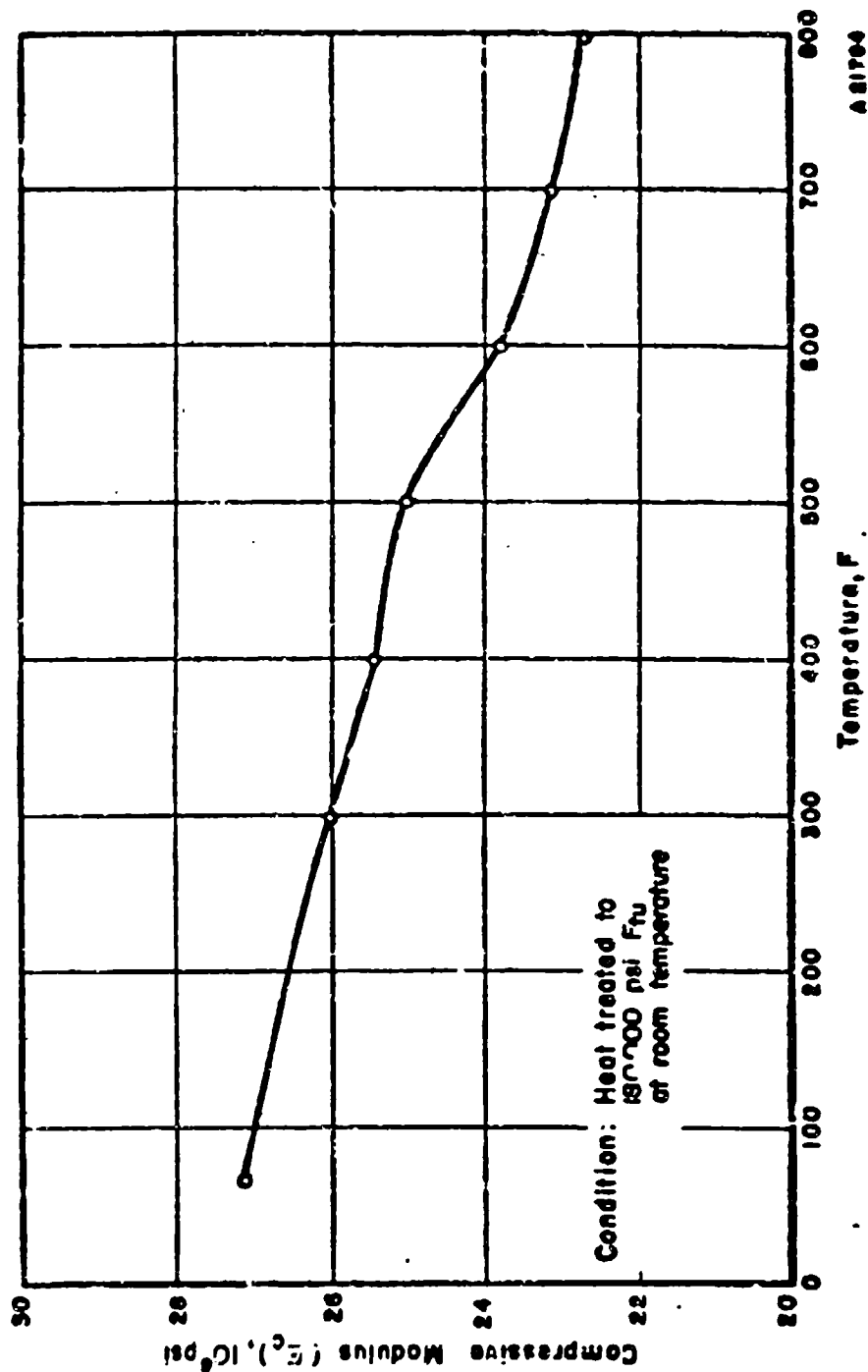


FIGURE 112. COMPRESSIVE MODULUS (E_c) OF AM-350 STAINLESS STEEL AT ELEVATED TEMPERATURE

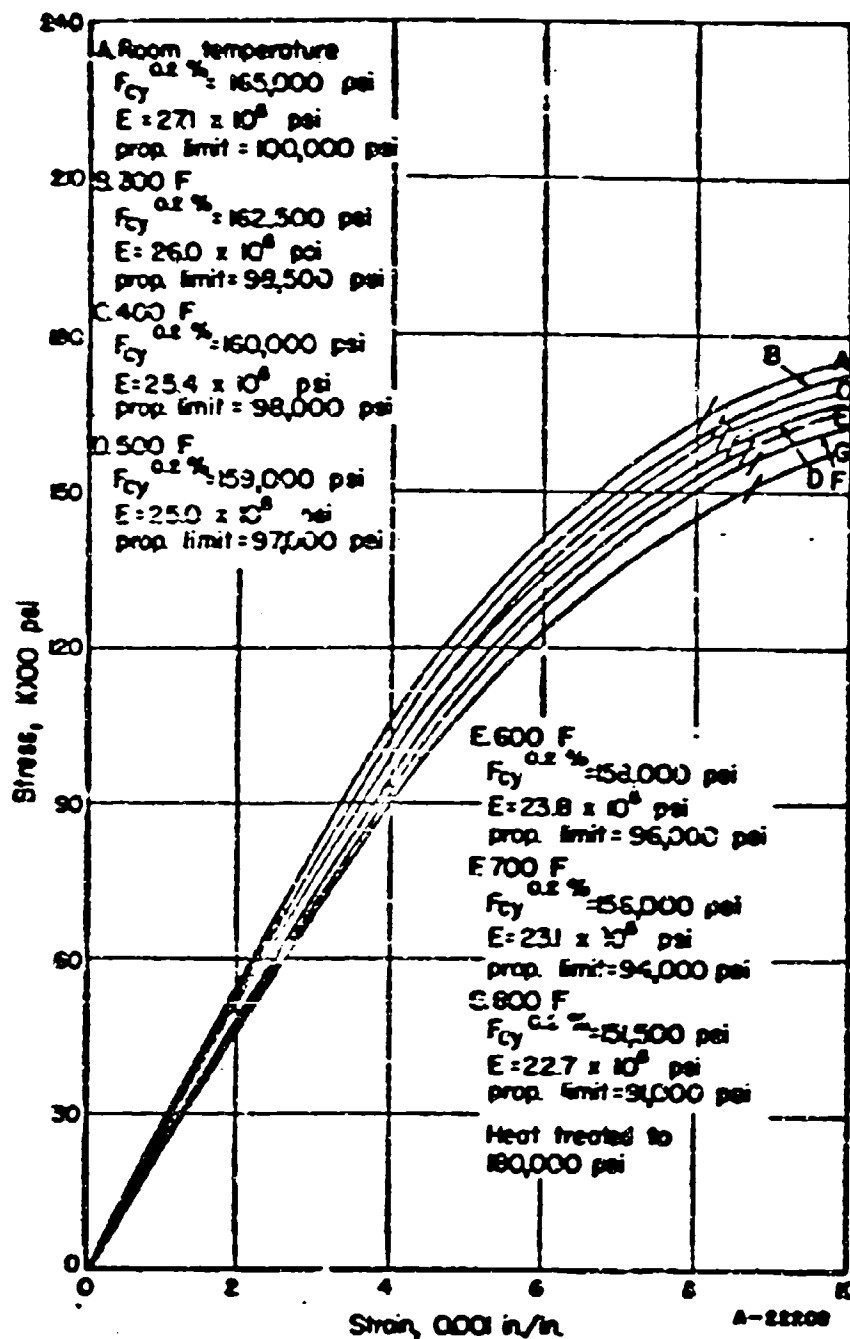


FIGURE 113. COMPRESSIVE STRESS-STRAIN CURVES FOR
 AM-350 STAINLESS STEEL AT ROOM AND
 ELEVATED TEMPERATURE

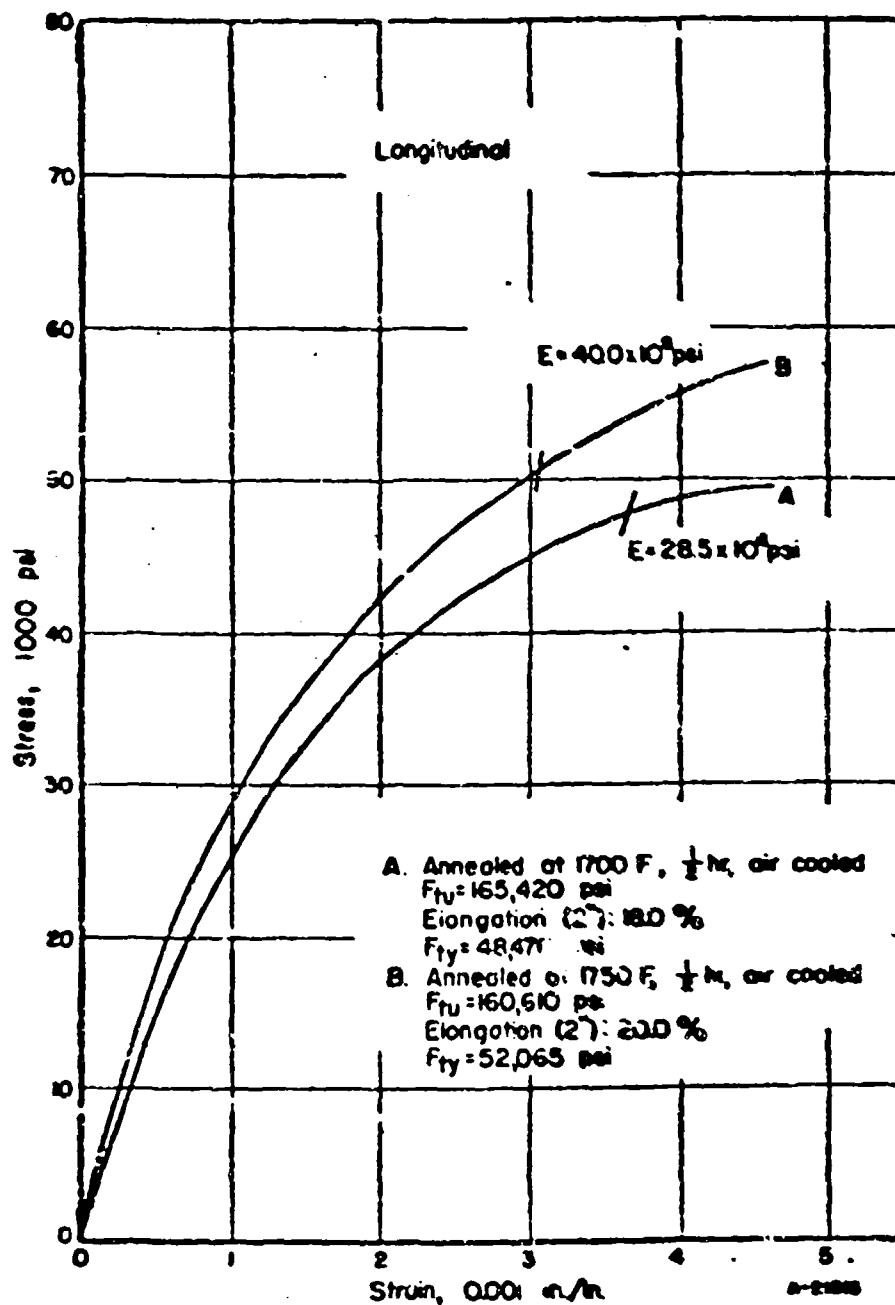


FIGURE 114. EFFECT OF ANNEALING AT 1700 F AND 1750 F ON THE TENSILE STRESS-STRAIN CURVE OF AM-350 STAINLESS STEEL AT ROOM TEMPERATURE (LONGITUDINAL PROPERTY)

Ref. 85.

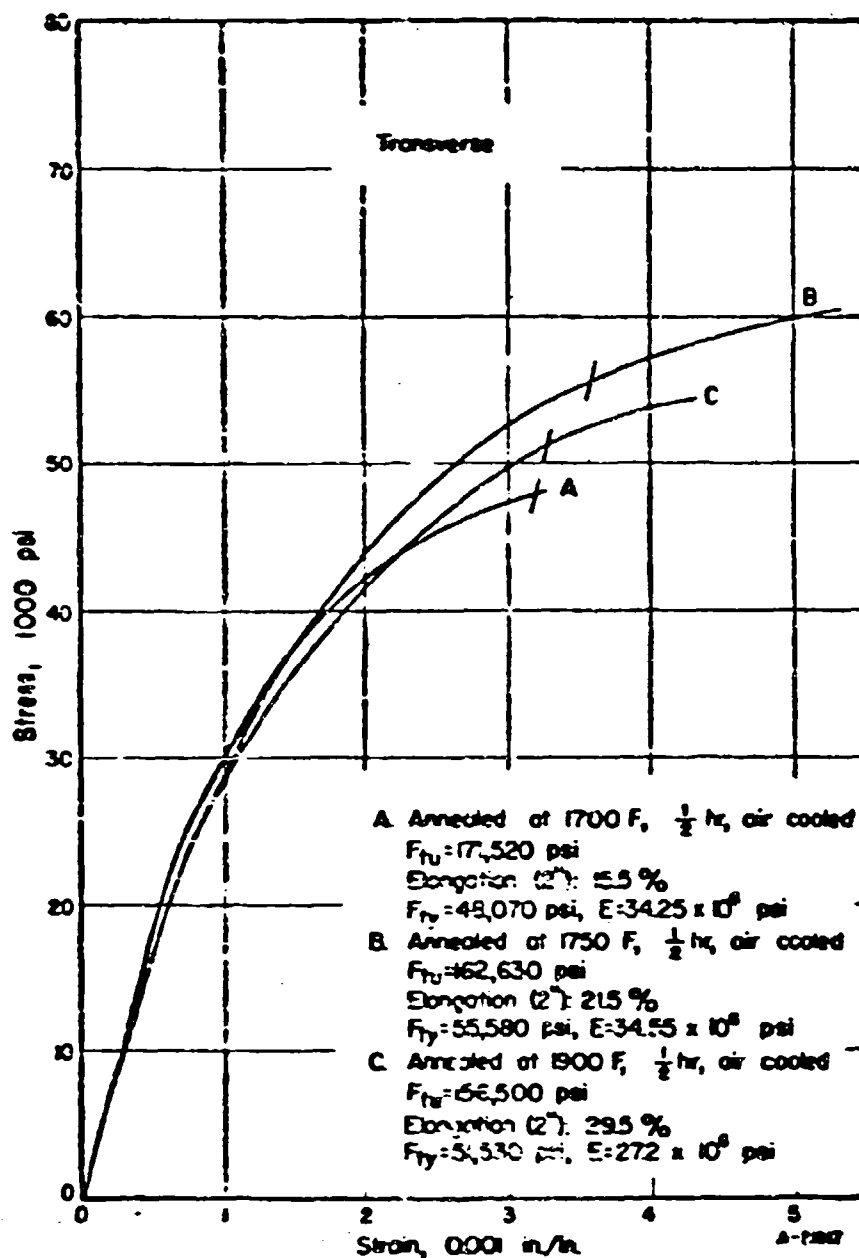


FIGURE 115. EFFECT OF ANNEALING AT 1700 F, 1750 F, AND 1900 F ON THE TENSILE STRESS-STRAIN CURVE OF 304-350 STAINLESS STEEL AT ROOM TEMPERATURE (TRANSVERSE PROPERTY)

Ref. 85.

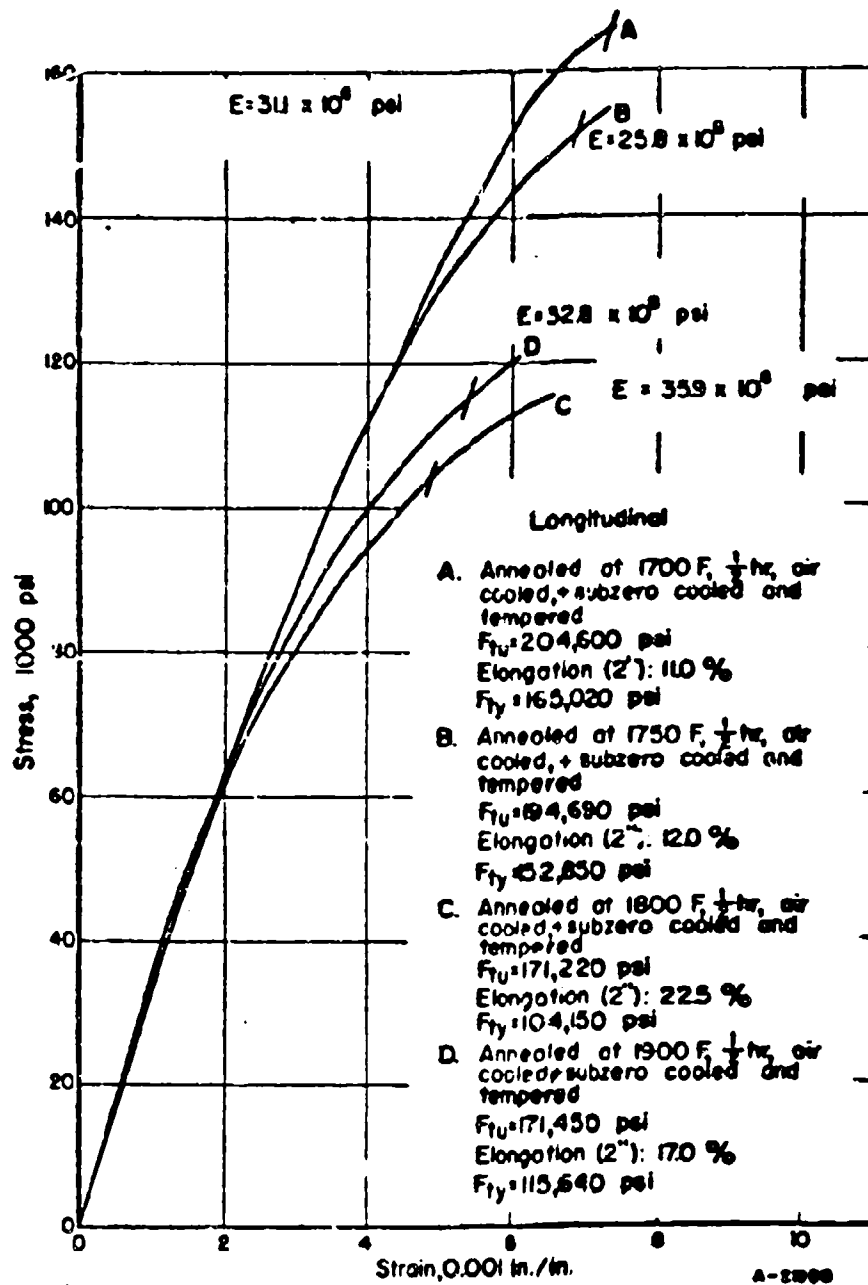


FIGURE 116. EFFECT OF ANNEALING, AT 1700 F, 1750 F, 1800 F, AND 1900 F SUBZERO COOLING, AND TEMPERING ON THE TENSILE STRESS-STRAIN CURVE OF AM-350 STAINLESS STEEL AT ROOM TEMPERATURE (LONGITUDINAL PROPERTY)

Ref. 85.

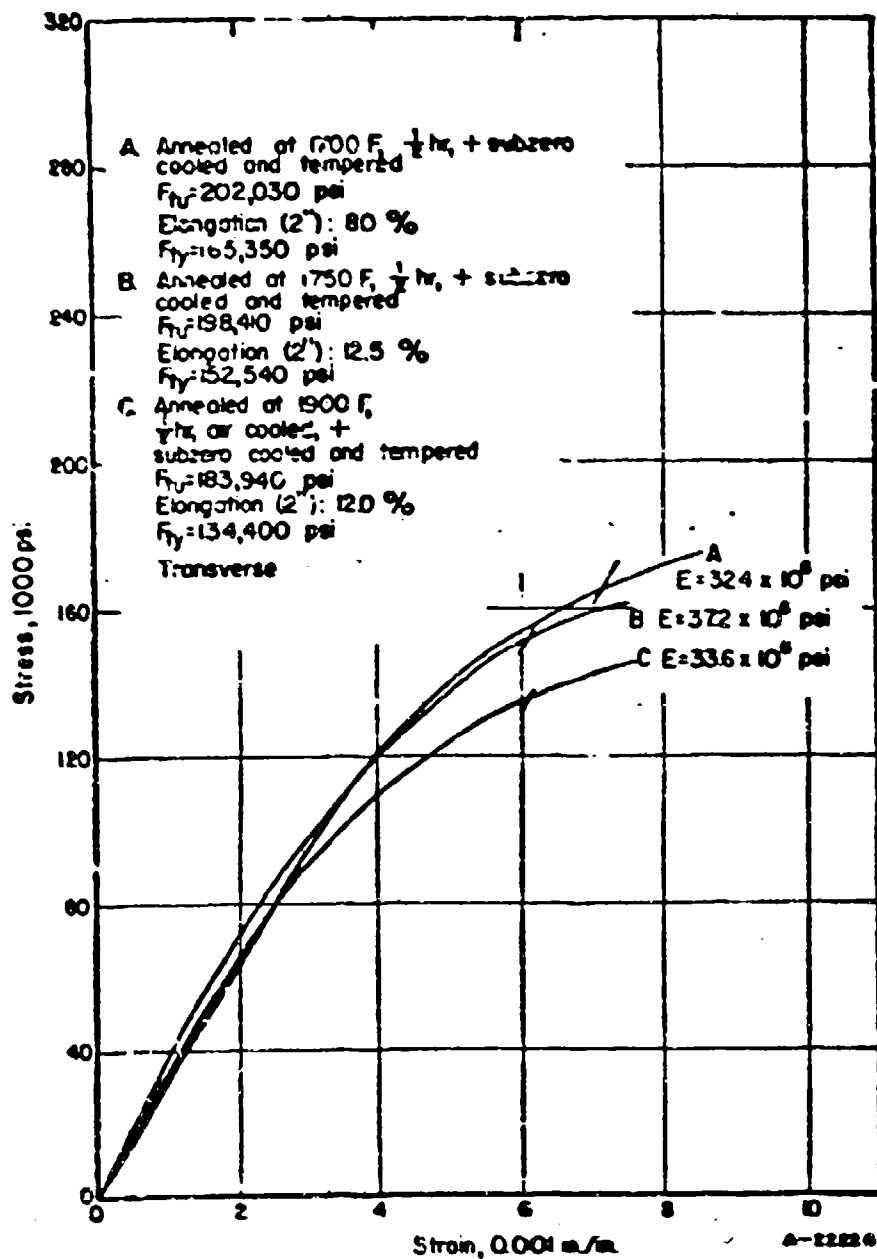


FIGURE 117. EFFECT OF ANNEALING, SUBZERO COOLING, AND TEMPERING ON THE TENSILE STRESS-STRAIN CURVE OF AM-350 STAINLESS STEEL AT ROOM TEMPERATURE (TRANSVERSE PROPERTY)

Ref. 25.

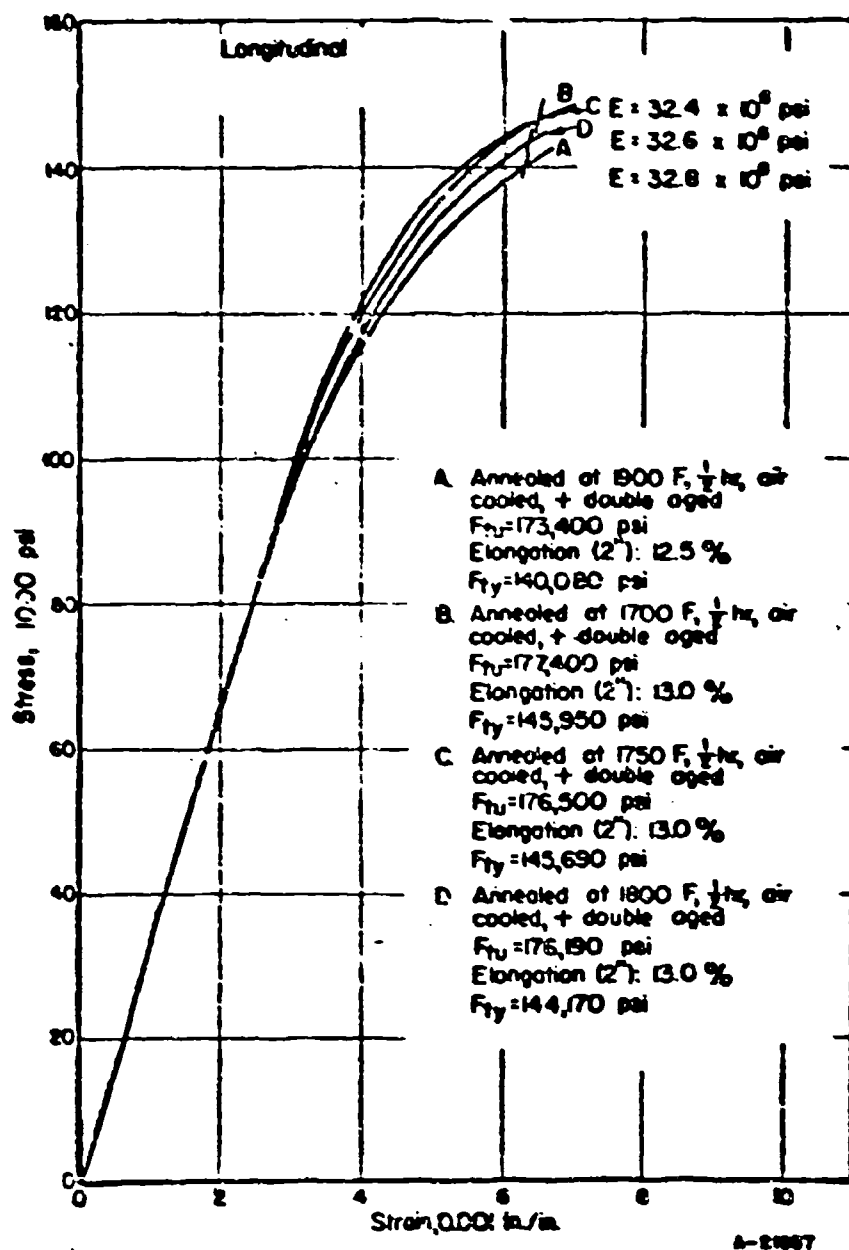


FIGURE 118. EFFECT OF ANNEALING, AT 1700 F, 1750 F, 1800 F, AND 1900 F AIR COOLING, AND DOUBLE AGING ON THE TENSILE STRESS-STRAIN CURVE OF AM-350 STAINLESS STEEL AT ROOM TEMPERATURE (LONGITUDINAL PROPERTY)

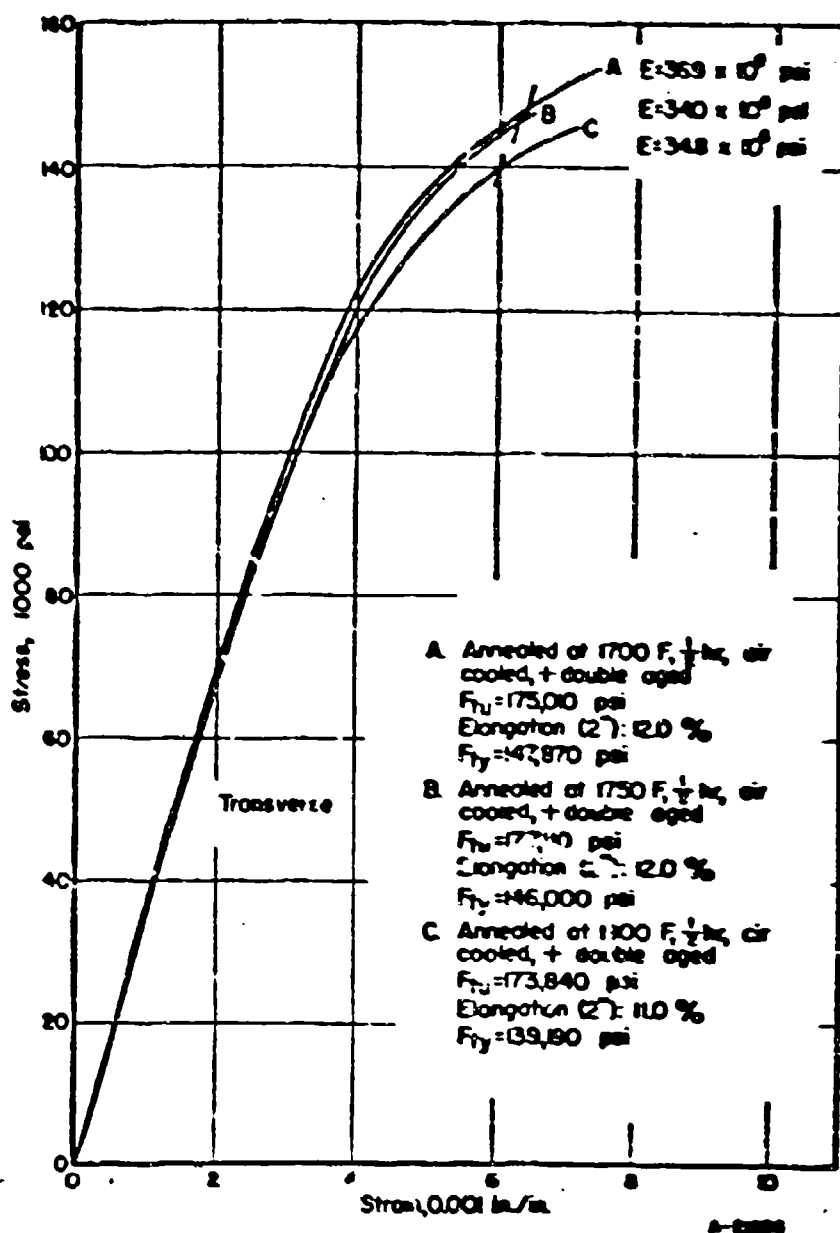


FIGURE 119. EFFECT OF ANNEALING, AT 1700 F, 1750 F, AND 1900 F AIR COOLING, AND DOUBLE AGING ON THE TENSILE STRESS-STRAIN CURVE OF AM-350 STAINLESS STEEL AT ROOM TEMPERATURE (TRANSVERSE PROPERTY)

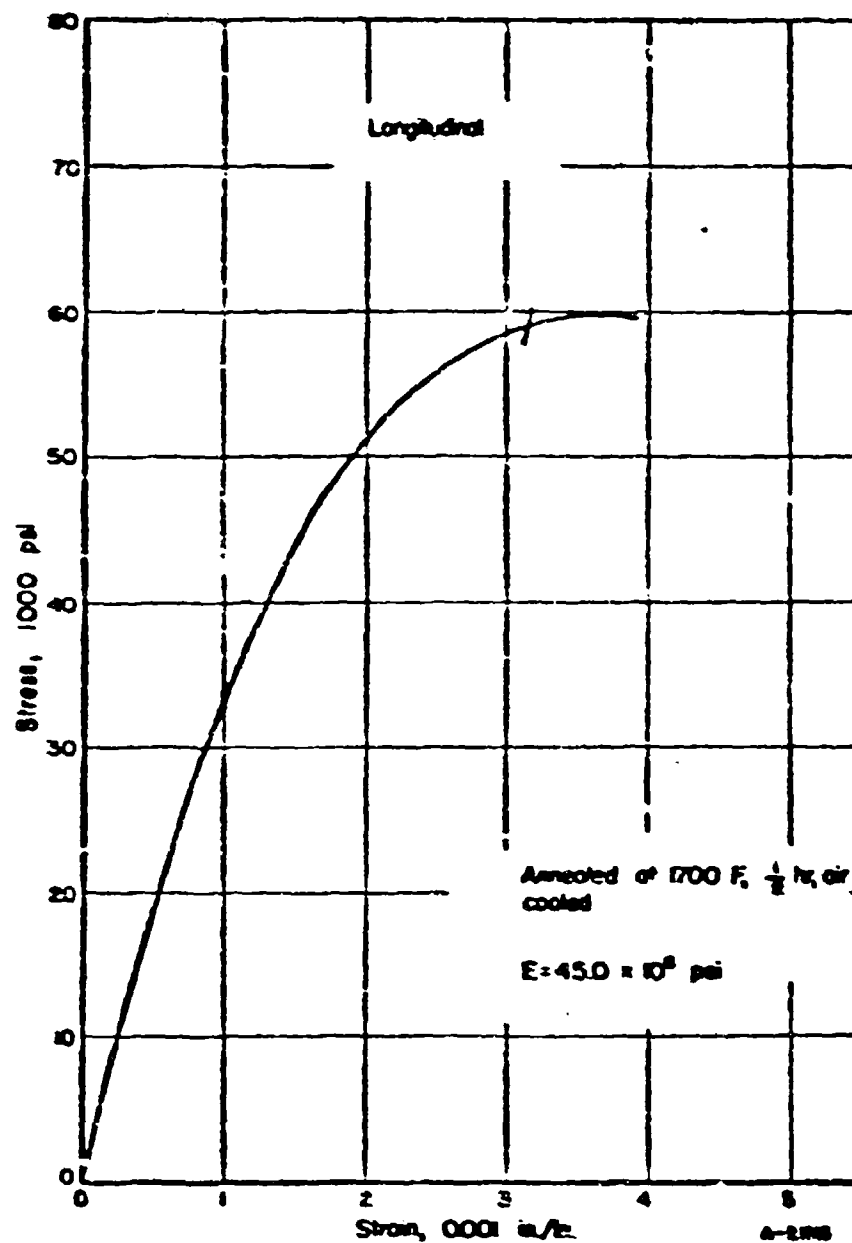


FIGURE 120. EFFECT OF ANNEALING AT 1700 F ON THE COMPRESSIVE STRESS-STRAIN CURVE OF AM-350 STAINLESS STEEL AT ROOM TEMPERATURE (LONGITUDINAL PROPERTY)

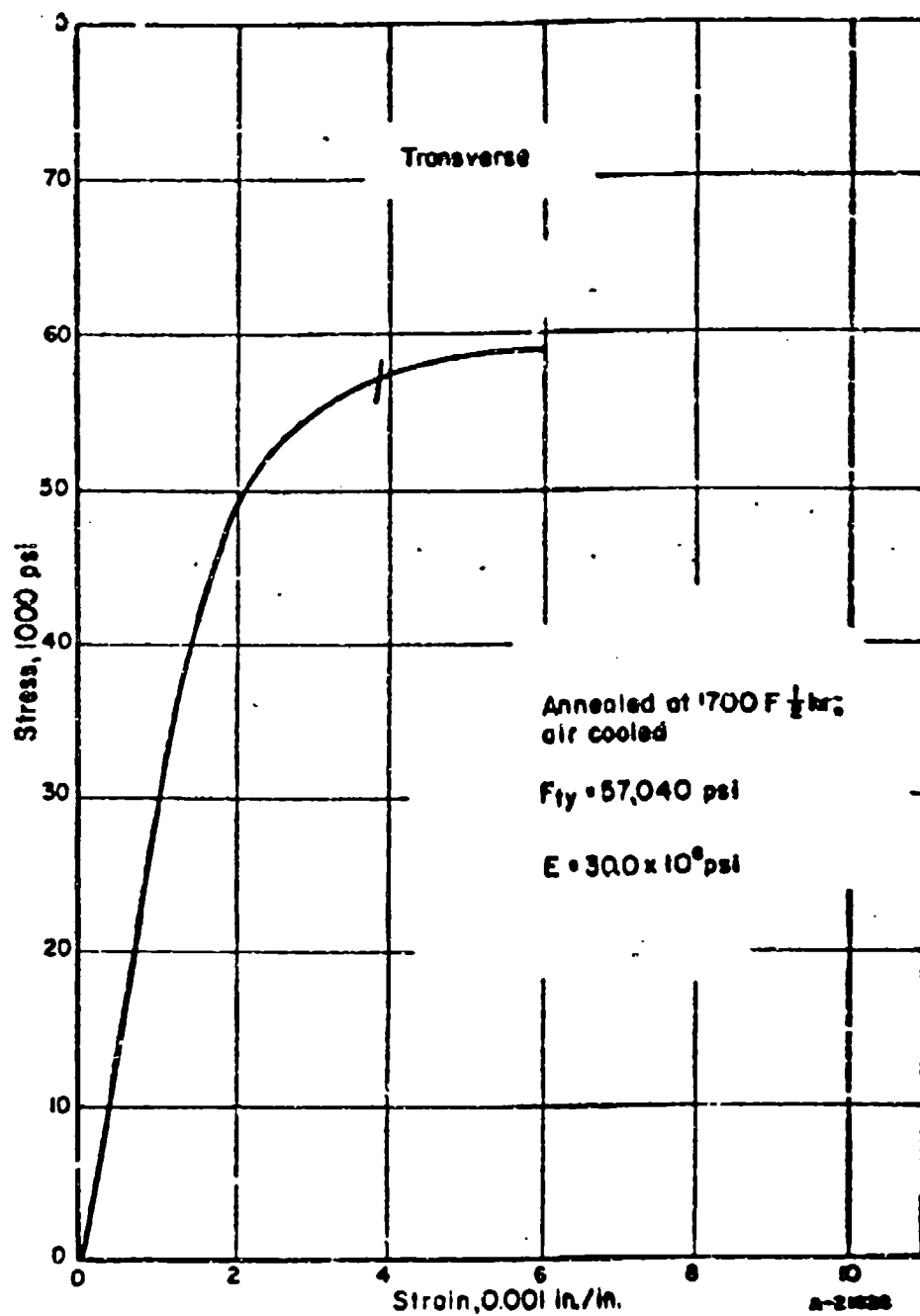


FIGURE 121. EFFECT OF ANNEALING AT 1700 F ON THE COMPRESSIVE STRESS-STRAIN CURVE OF AM-350 STAINLESS STEEL AT ROOM TEMPERATURE (TRANSVERSE PROPERTY)

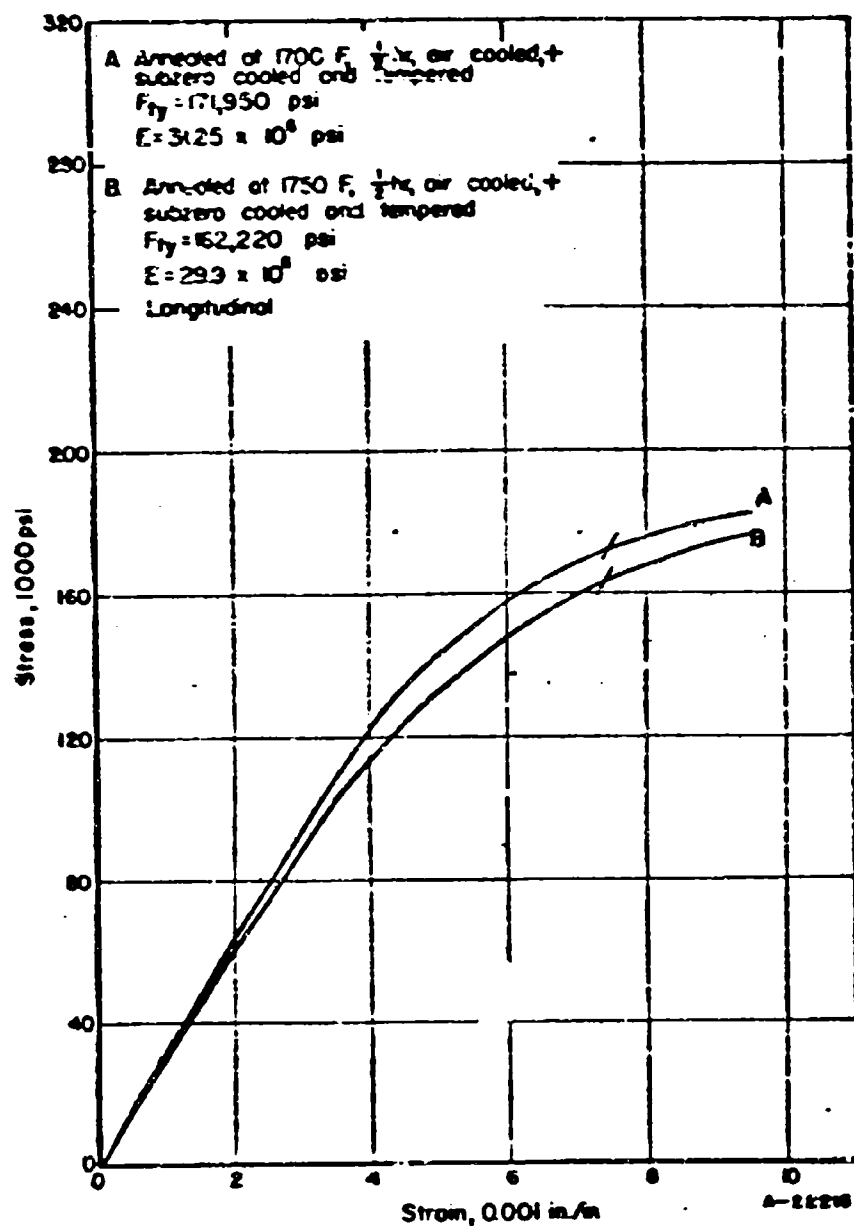


FIGURE 122. EFFECT OF ANNEALING, SUBZERO COOLING, AND TEMPERING ON THE COMPRESSIVE STRESS-STRAIN CURVE AM-350 STAINLESS STEEL AT ROOM TEMPERATURE (LONGITUDINAL PROPERTY)

Ref. 85.

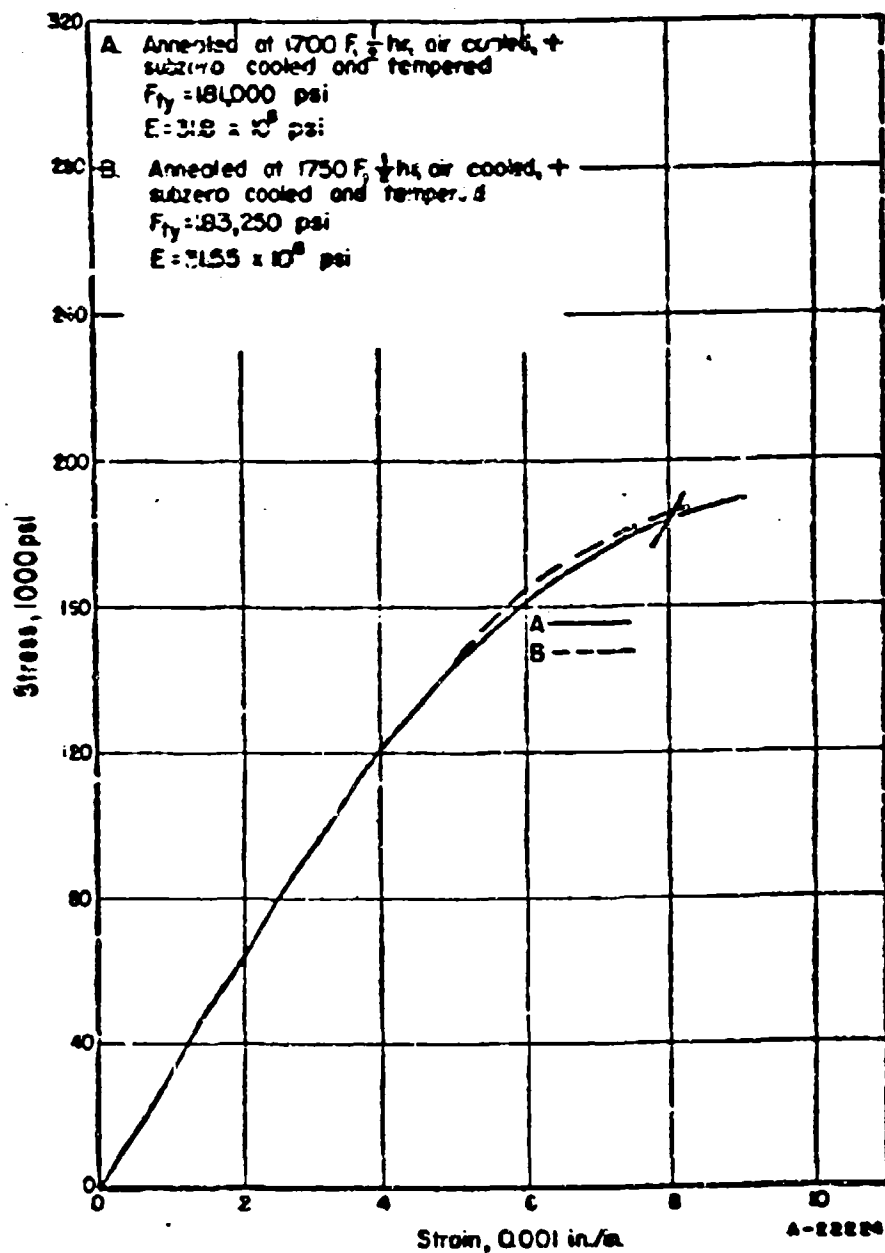


FIGURE 123. EFFECT OF ANNEALING, SUBZERO COOLING, AND TEMPERING ON THE COMPRESSIVE STRESS-STRAIN CURVE OF AM-350 STAINLESS STEEL AT ROOM TEMPERATURE (TRANSVERSE PROPERTY)

Ref. 85.

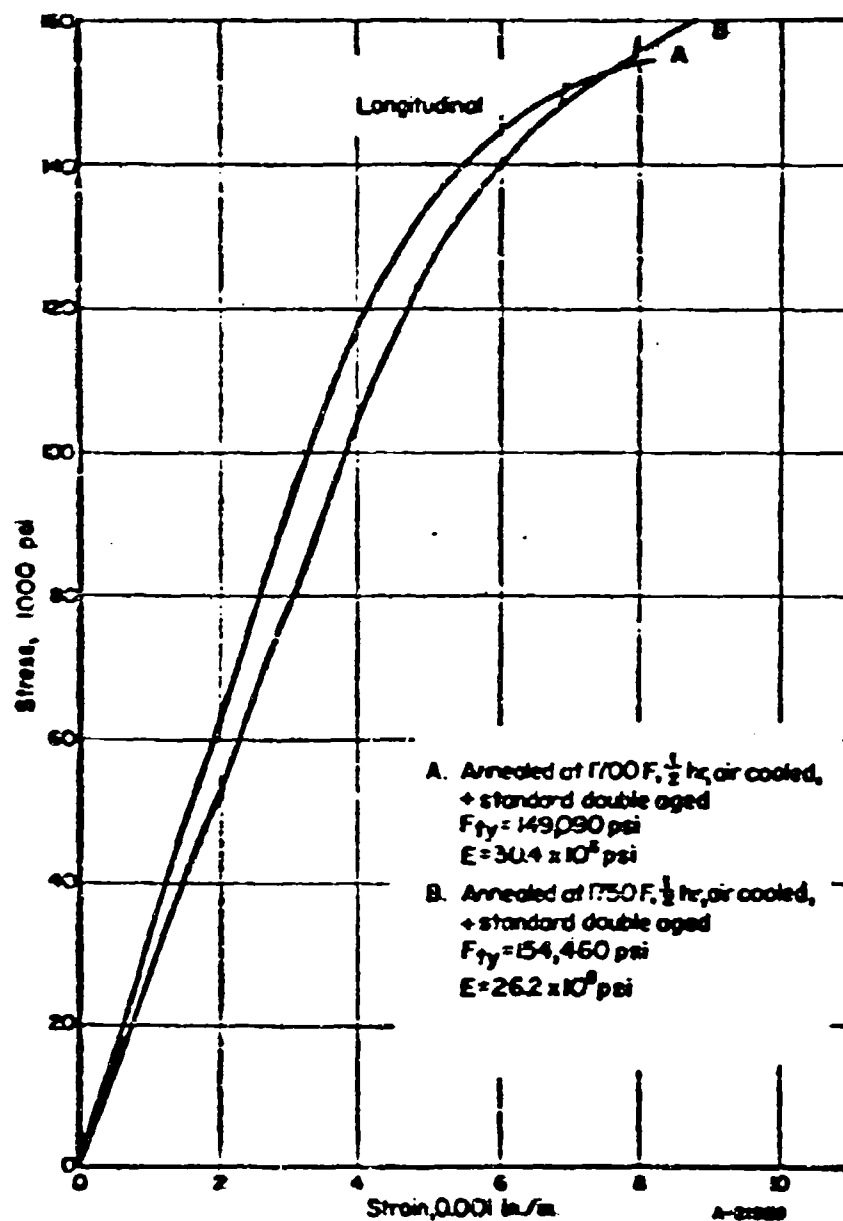


FIGURE 12. EFFECT OF ANNEALING AT 1700 F AND 1750 F AND STANDARD DOUBLE AGING ON THE COMPRESSIVE STRESS-STRAIN CURVE OF AM-350 STAINLESS STEEL AT ROOM TEMPERATURE (LONGITUDINAL PROPERTY)

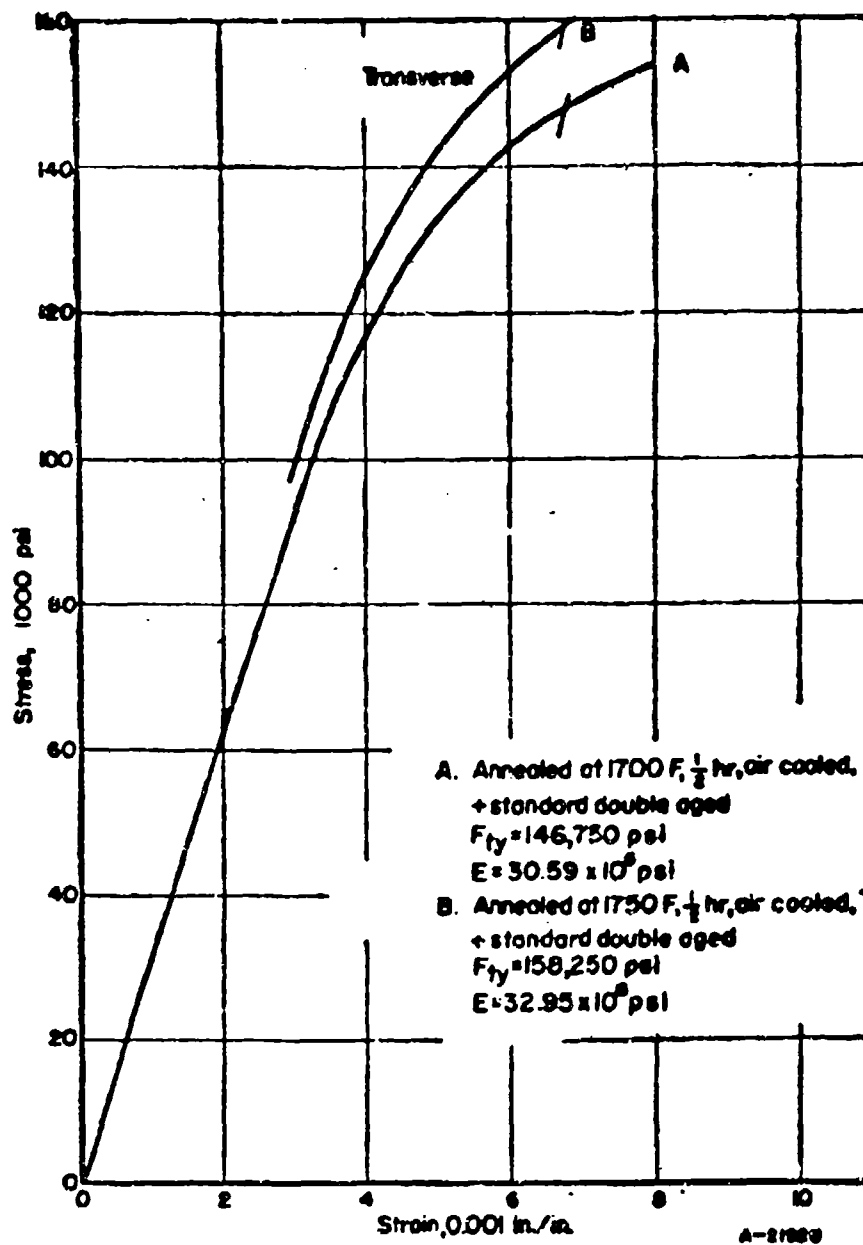


FIGURE 125. EFFECT OF ANNEALING AT 1700 F AND 1750 F AND STANDARD DOUBLE AGING ON THE COMPRESSIVE STRESS-STRAIN CURVE OF AM-350 STAINLESS STEEL AT ROOM TEMPERATURE (TRANSVERSE PROPERTY)

17-4PH STAINLESS STEEL

17-4PH has a composition that has been termed a "severely unbalanced" AISI 301. The austenitic phase is so unstable that it transforms to martensite at about 200 to 300 F, upon cooling from the annealing temperature. Aging at about 900 to 1000 F promotes precipitation of intermetallic compounds from the martensite. The nominal composition of 17-4PH is shown in Table 7.

TABLE 7. NOMINAL CHEMICAL COMPOSITION
OF 17-4PH STAINLESS STEEL

Element	Weight Per Cent
Chromium	16.50
Nickel	4.00
Copper	4.00
Columbium (niobium) + tantalum	0.35
Carbon, maximum	0.07
Iron	Balance

The short-time, elevated-temperature properties of 17-4PH are shown in the following curves:

- (1) Tensile properties, Figures 126 through 129 and 138
- (2) Compressive properties, Figures 130 and 131
- (3) Shear properties, Figures 132 and 133
- (4) Bearing properties, Figures 134 through 137
- (5) Modulus of elasticity, Figures 139 and 141
- (6) Stress-strain curves, Figures 140 and 142

Data are available on 17-4PH for all surveyed strength properties.

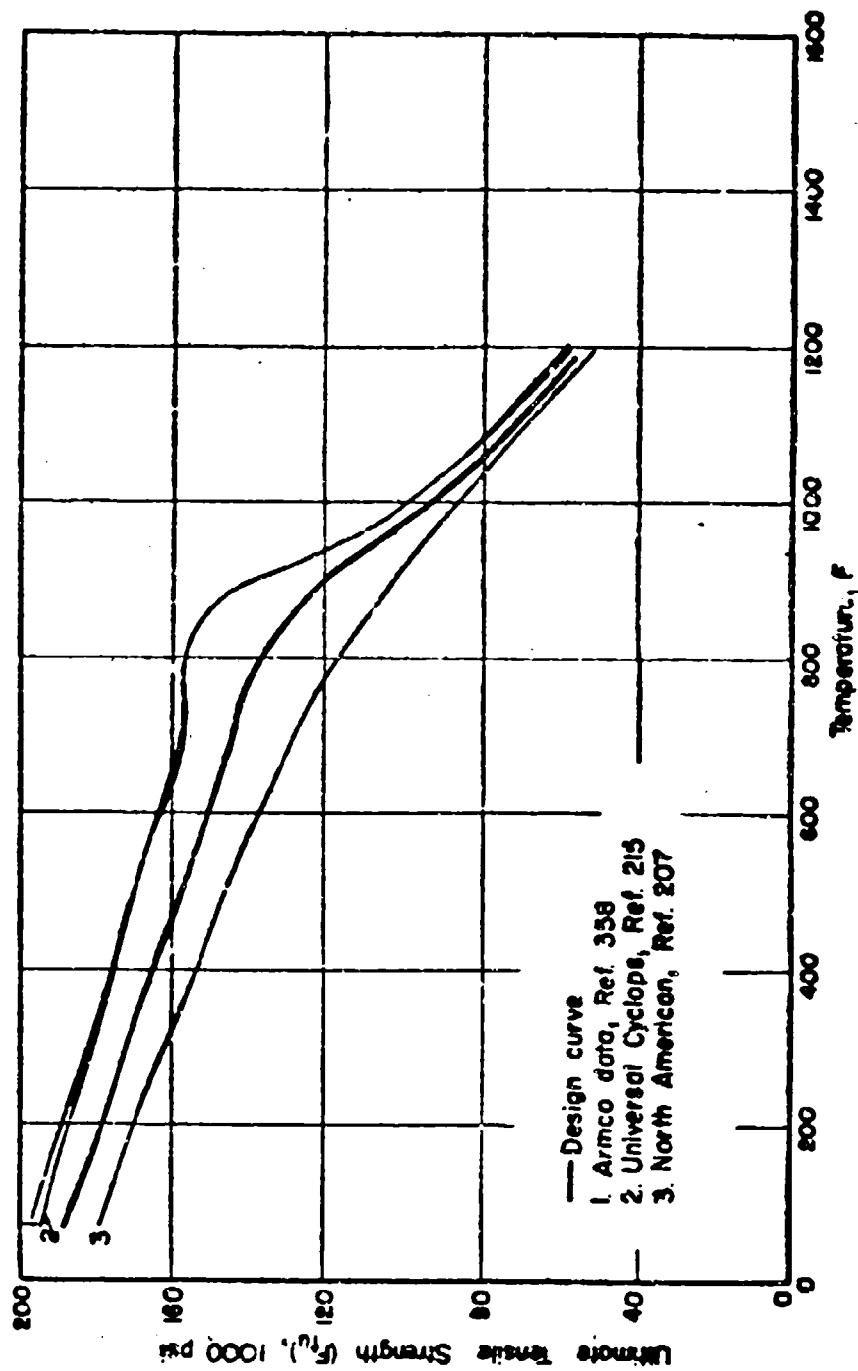


FIGURE 126. TENSILE STRENGTH (F_u) OF 17-4PH STAINLESS STEEL AT ELEVATED TEMPERATURE

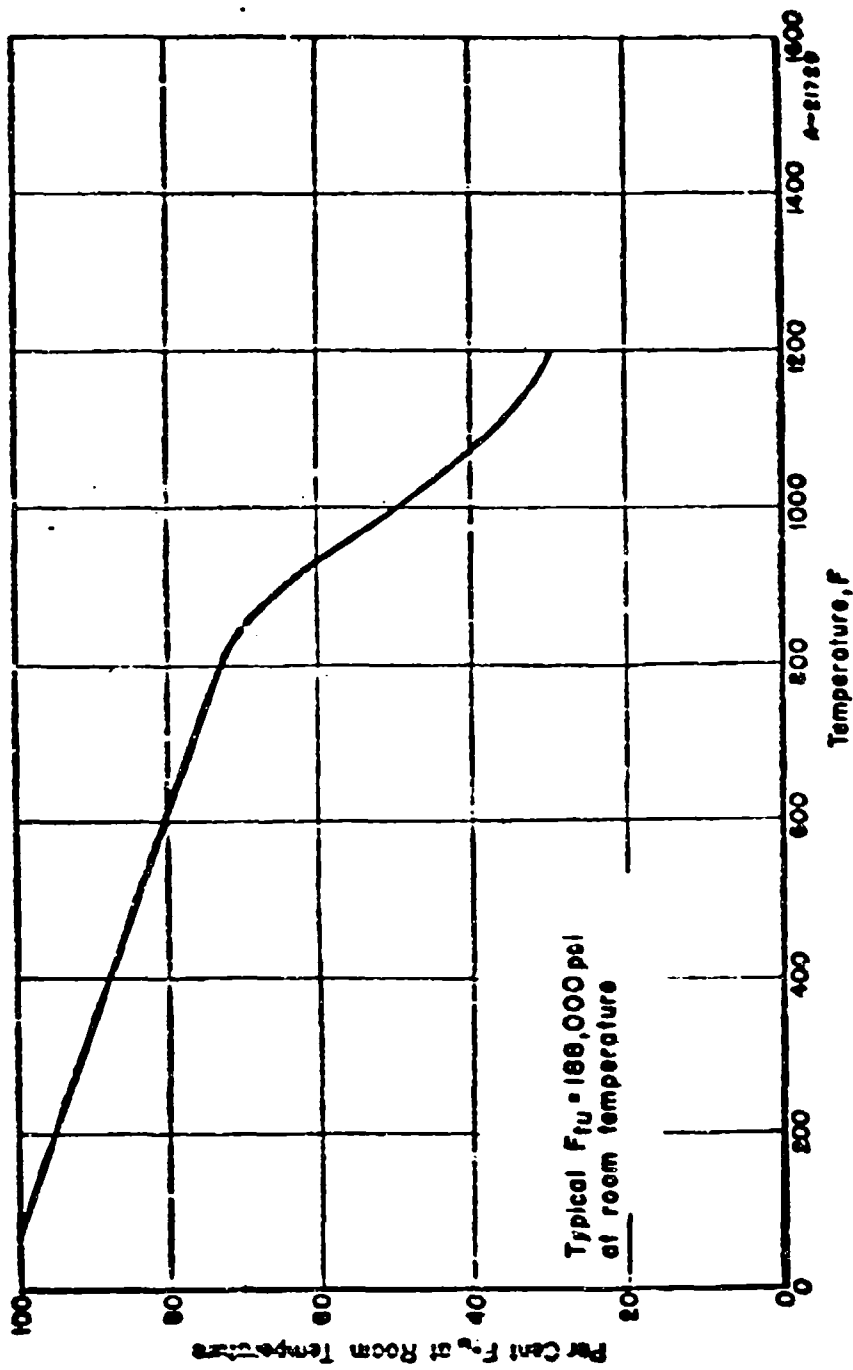


FIGURE 127. DESIGN CURVE FOR TENSILE STRENGTH (F_u) OF 17-4PH STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 207, 215, 358.

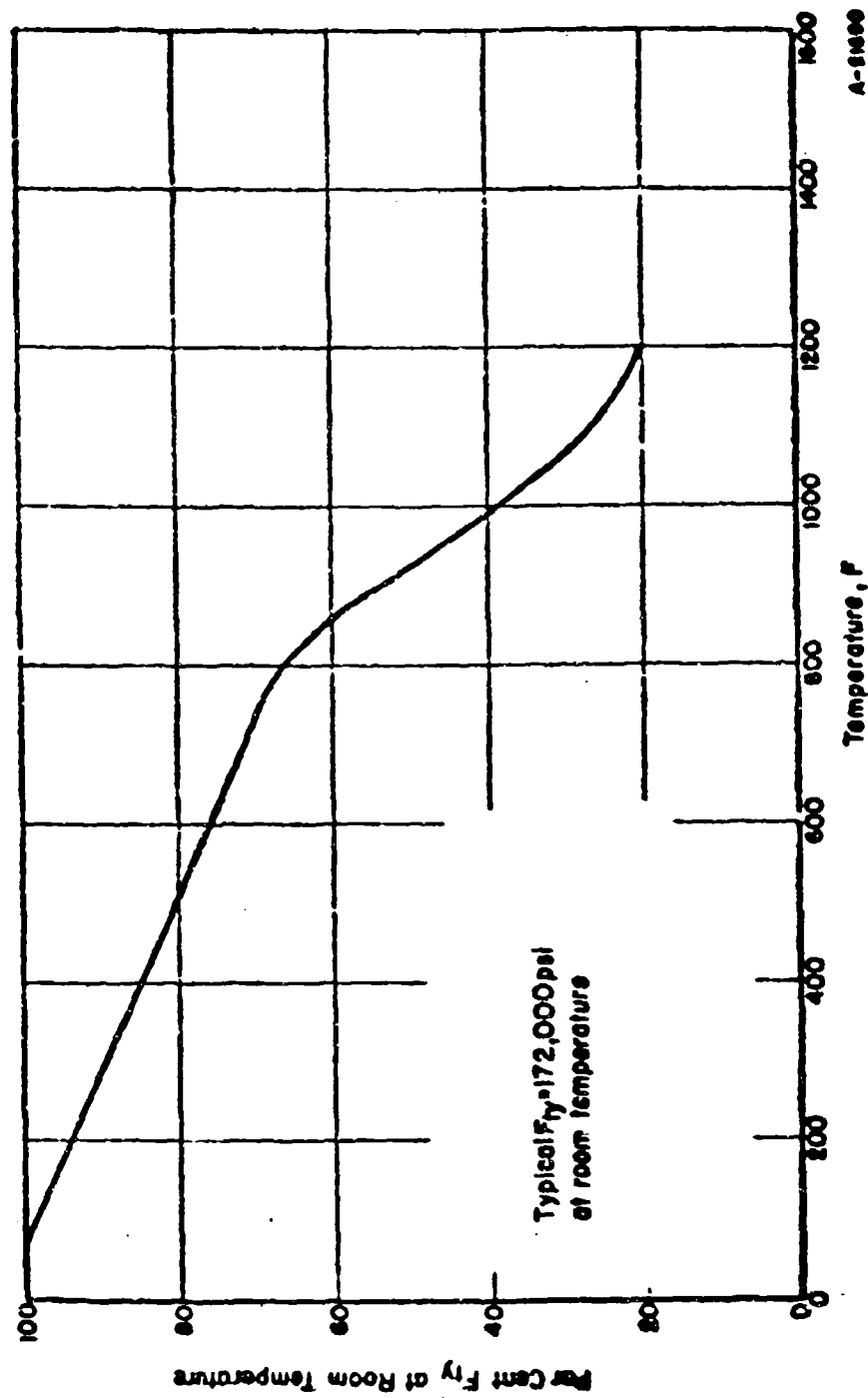


FIGURE 129. DESIGN CURVE FOR TENSILE YIELD STRENGTH (F_y) OF 17-4PH STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 207, 215, 380.

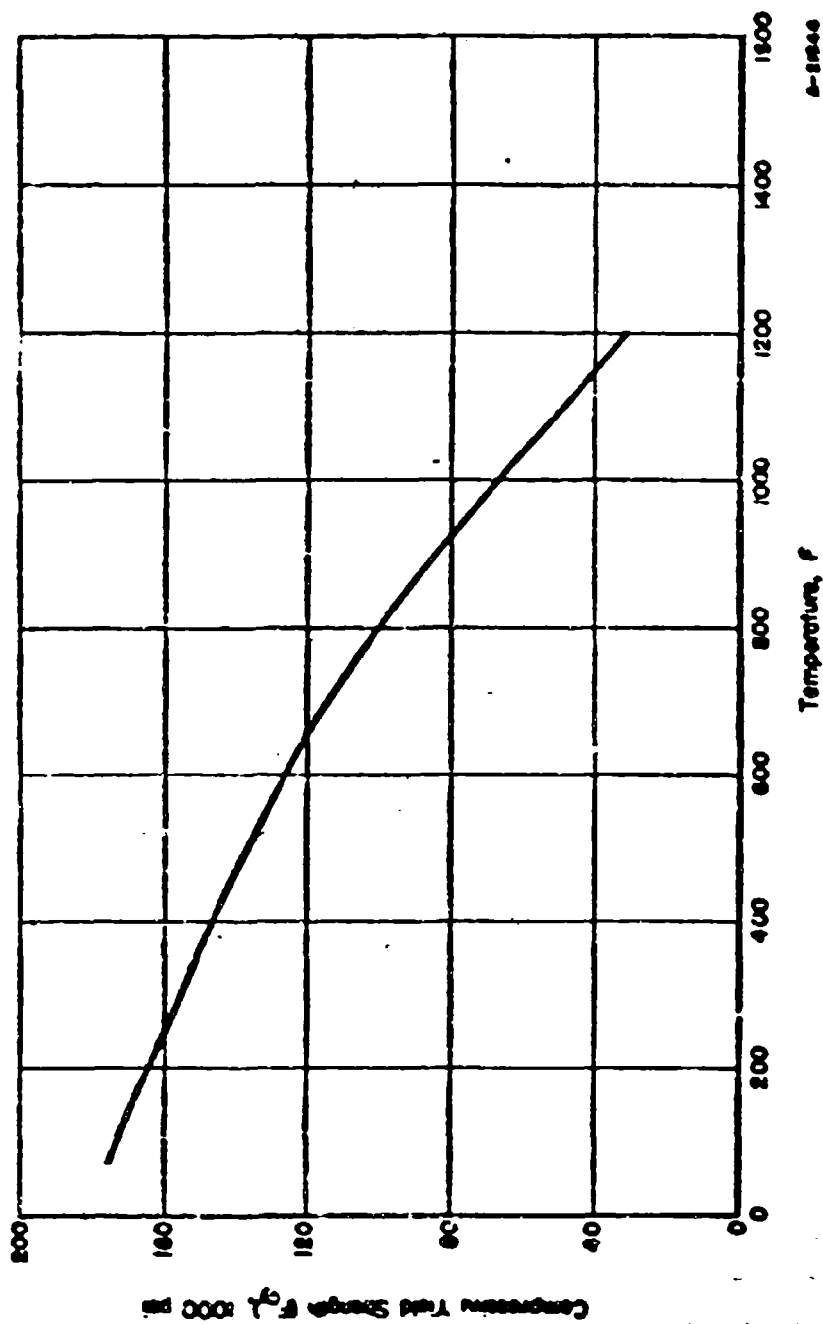


FIGURE 130. COMPRESSIVE YIELD STRENGTH (F_y) OF 17-4PH STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 207.

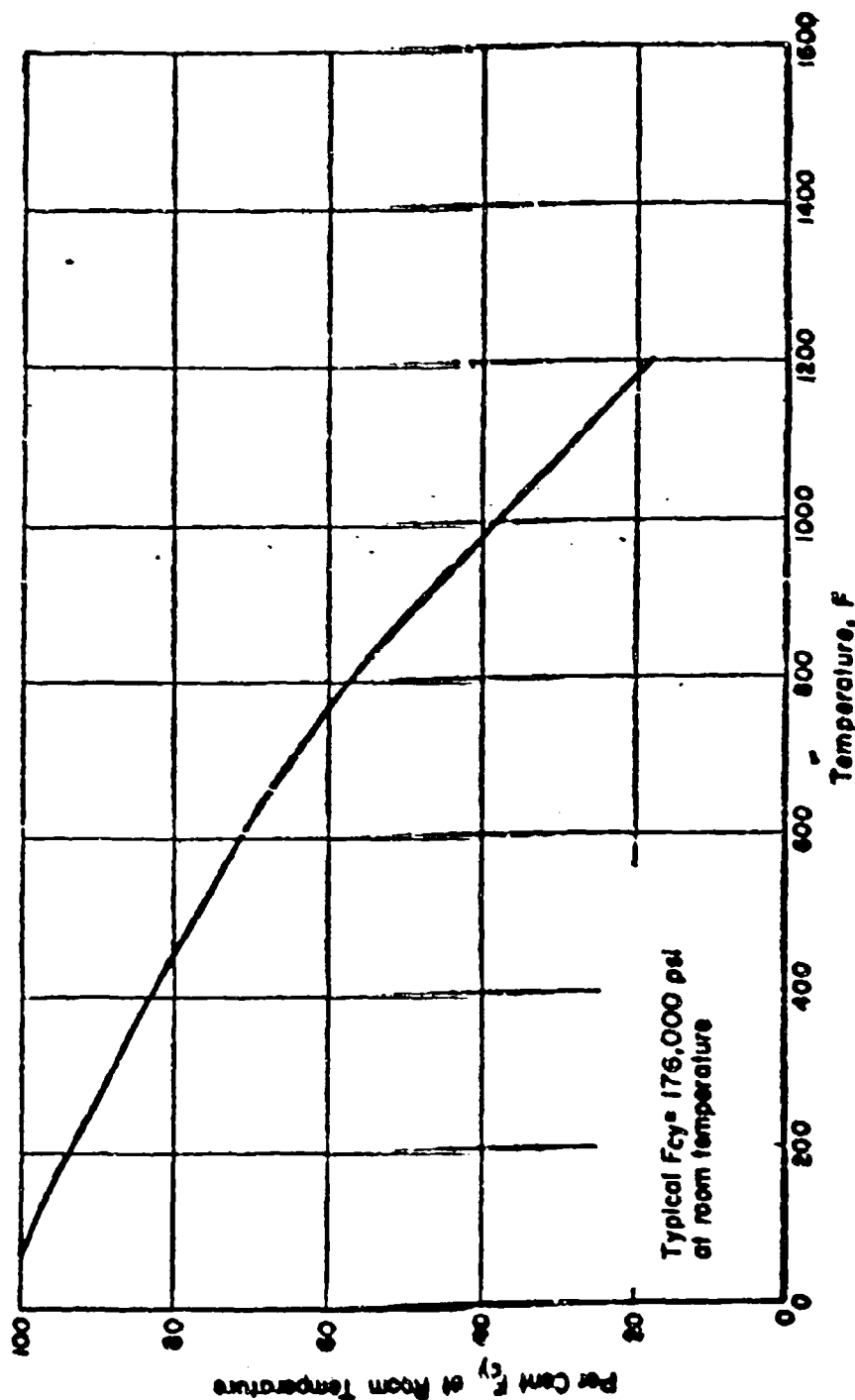


FIGURE 131. DESIGN CURVE FOR COMPRESSIVE YIELD STRENGTH (F_{cy}) OF 17-4PH STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 207.

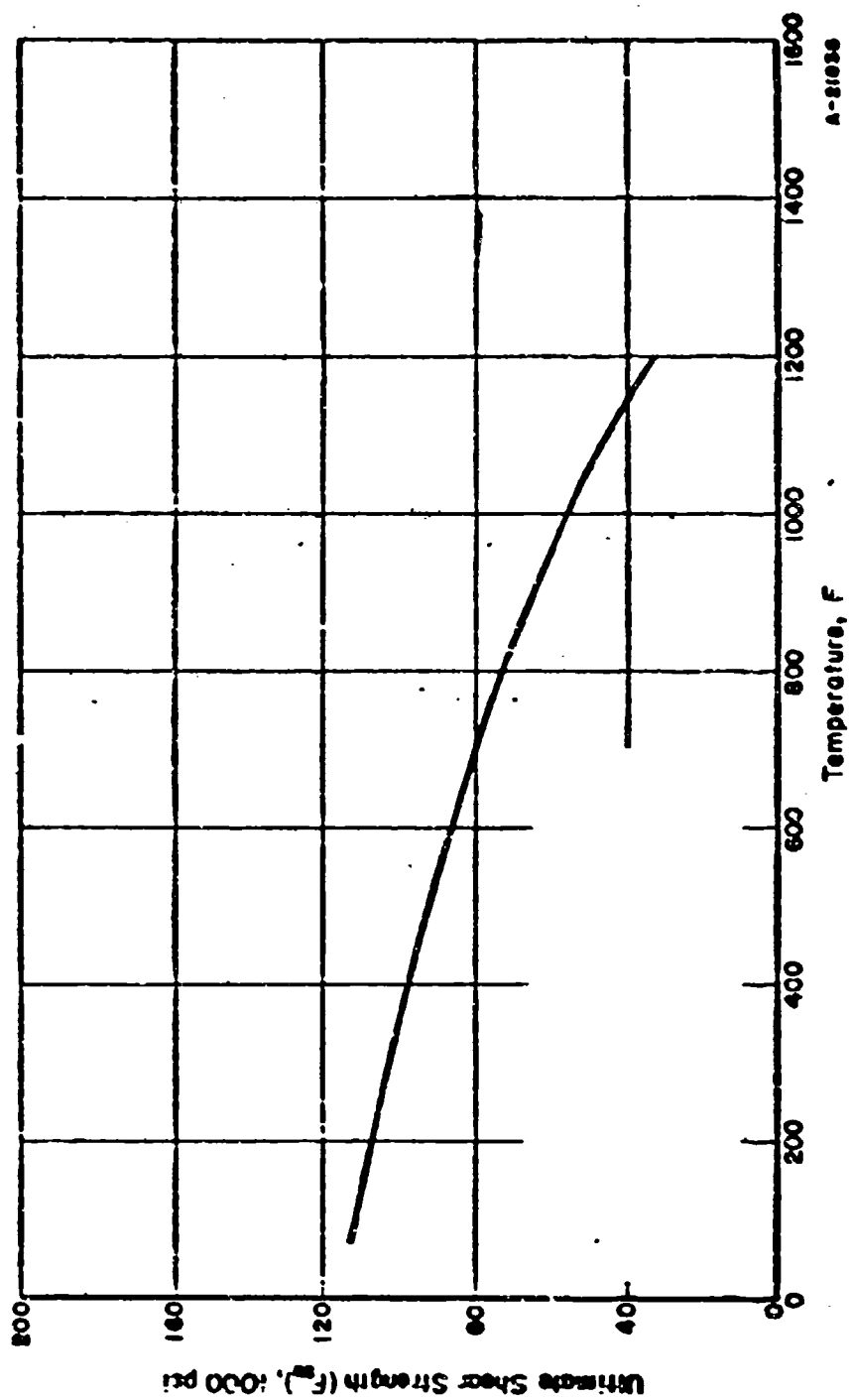


FIGURE 132. SHEAR STRENGTH (F_{su}) OF 17-4PH STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 207.

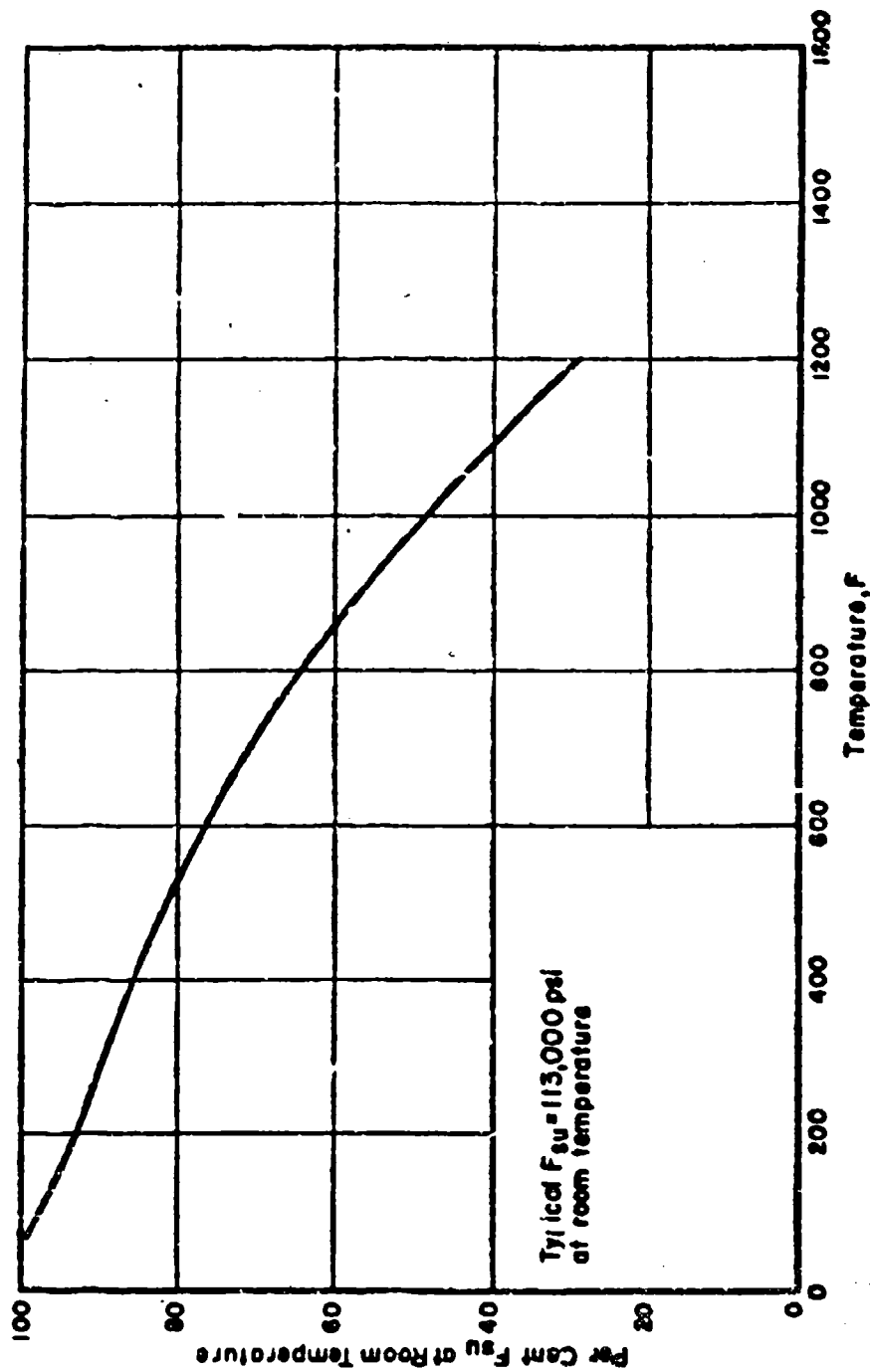


FIGURE 133. DESIGN CURVE FOR SHEAR STRENGTH (F_{su}) OF 17-4PH STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 207.

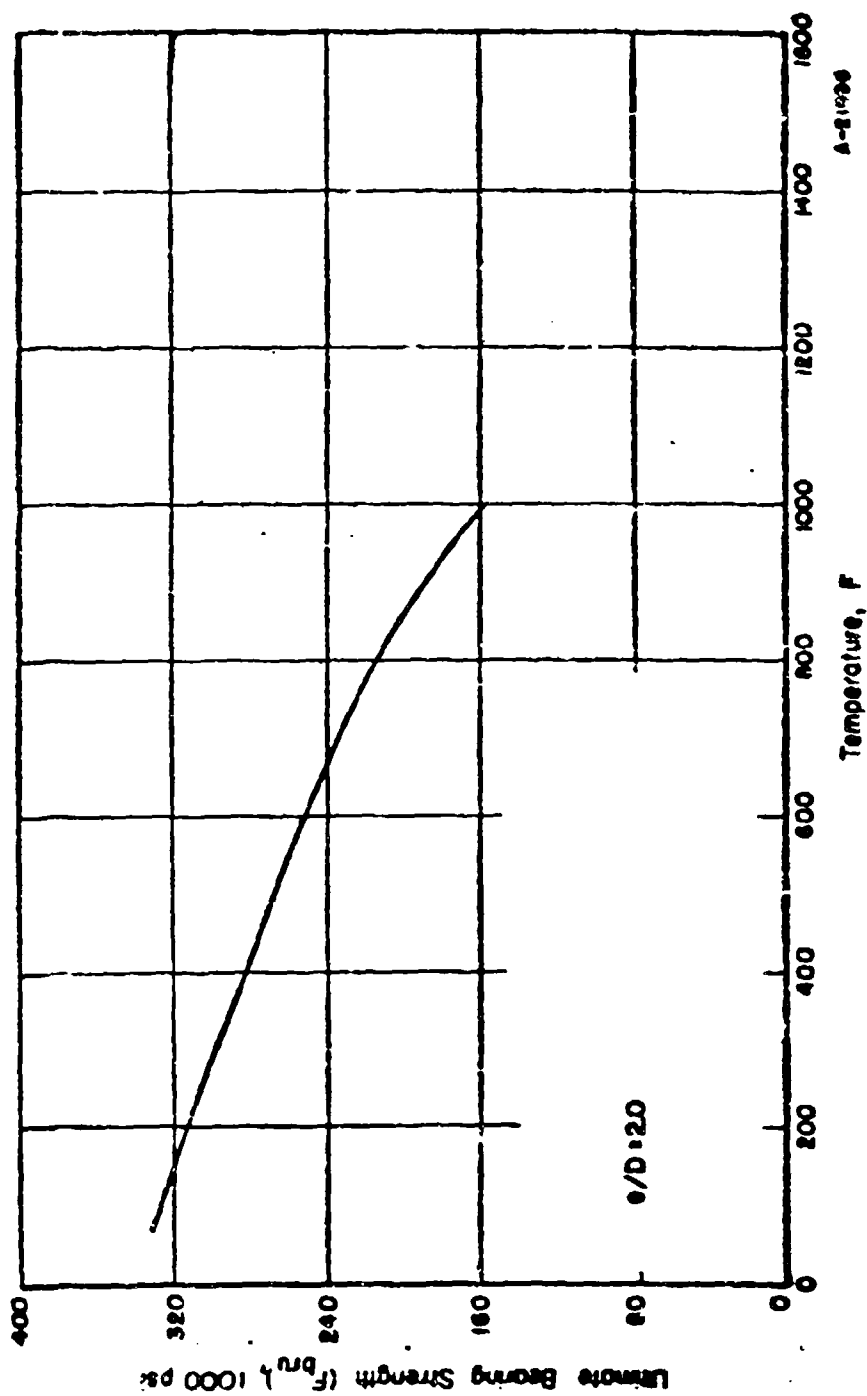


FIGURE 134. BEARING STRENGTH (F_{bru}) OF 17-4PH STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 207.

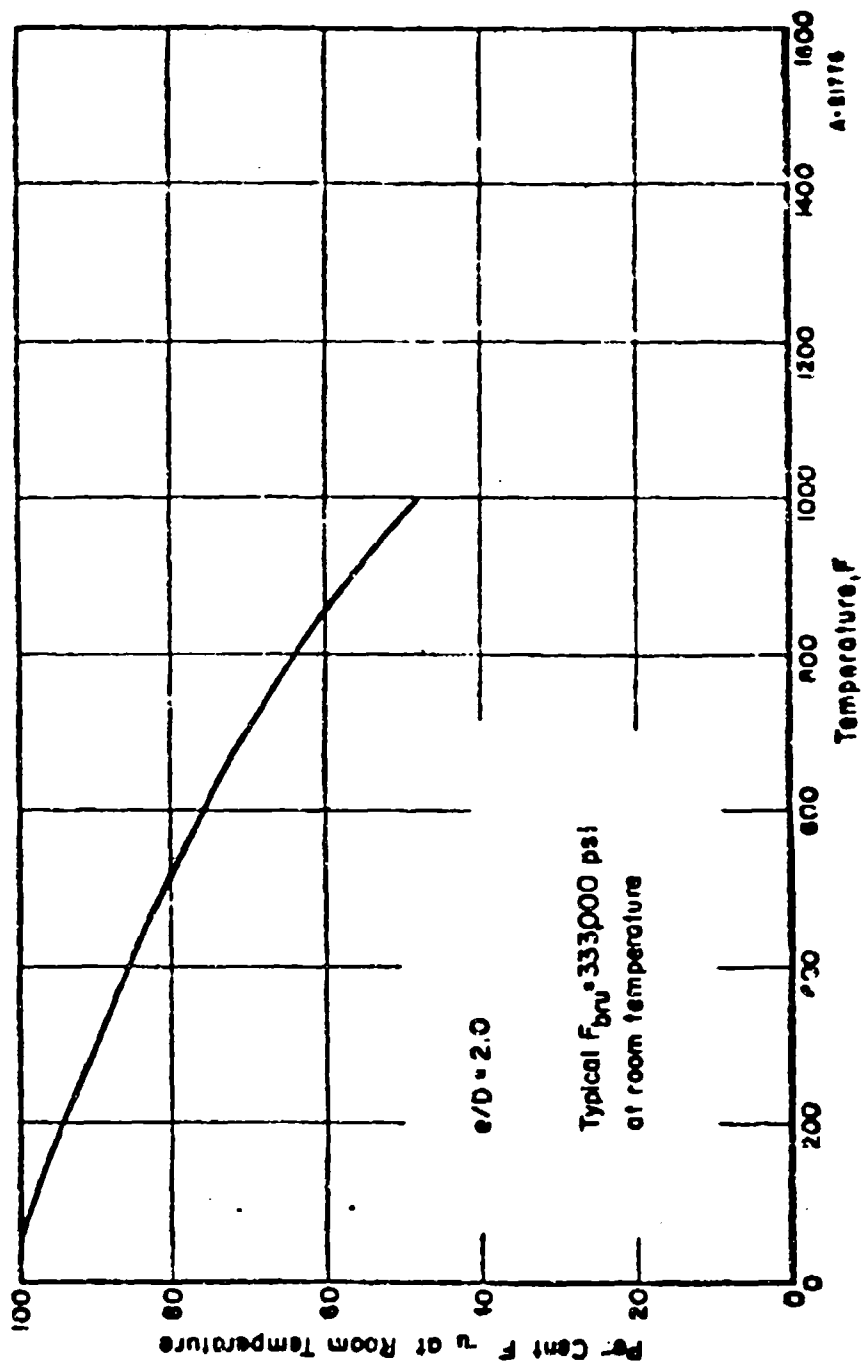


FIGURE 135. DESIGN CURVE FOR BEARING STRENGTH (F_{bru}) OF 17-4PH STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 207.

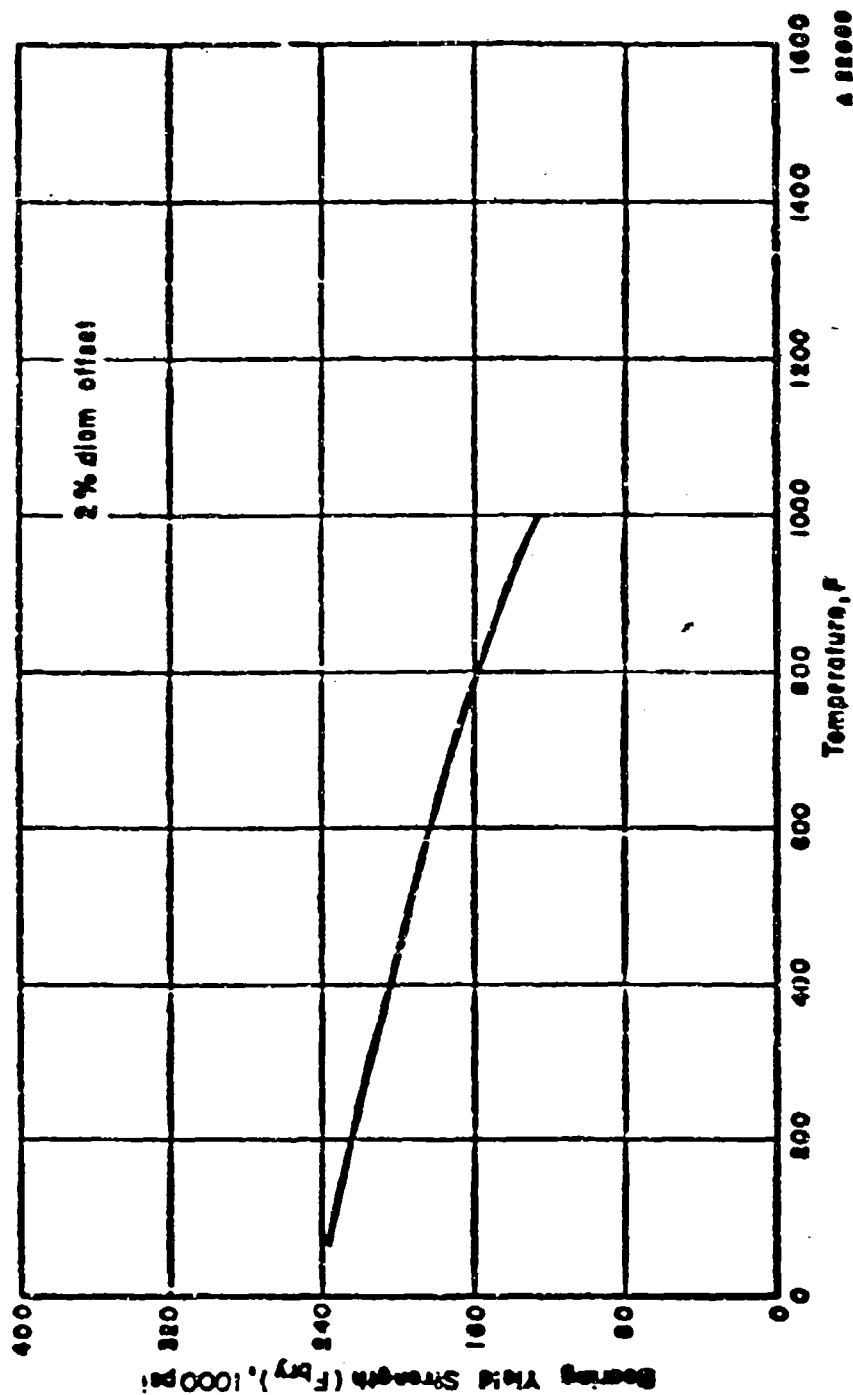


FIGURE 136. BEARING YIELD STRENGTH (F_{by}) OF 17-4PH STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 207.

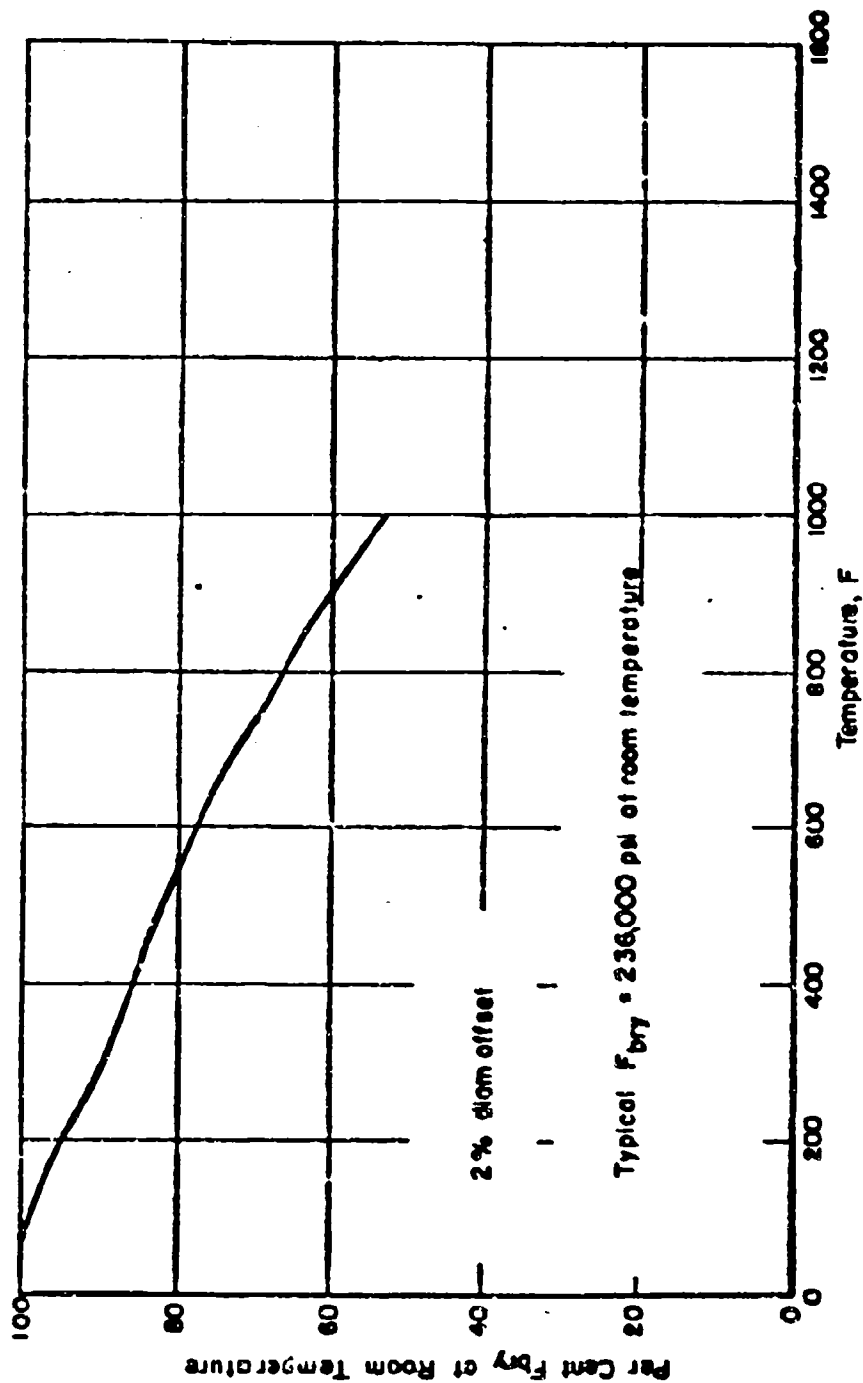


FIGURE 137. DESIGN CURVE FOR BEARING YIELD STRENGTH (F_{bry}) OF 17-4PH STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 207.

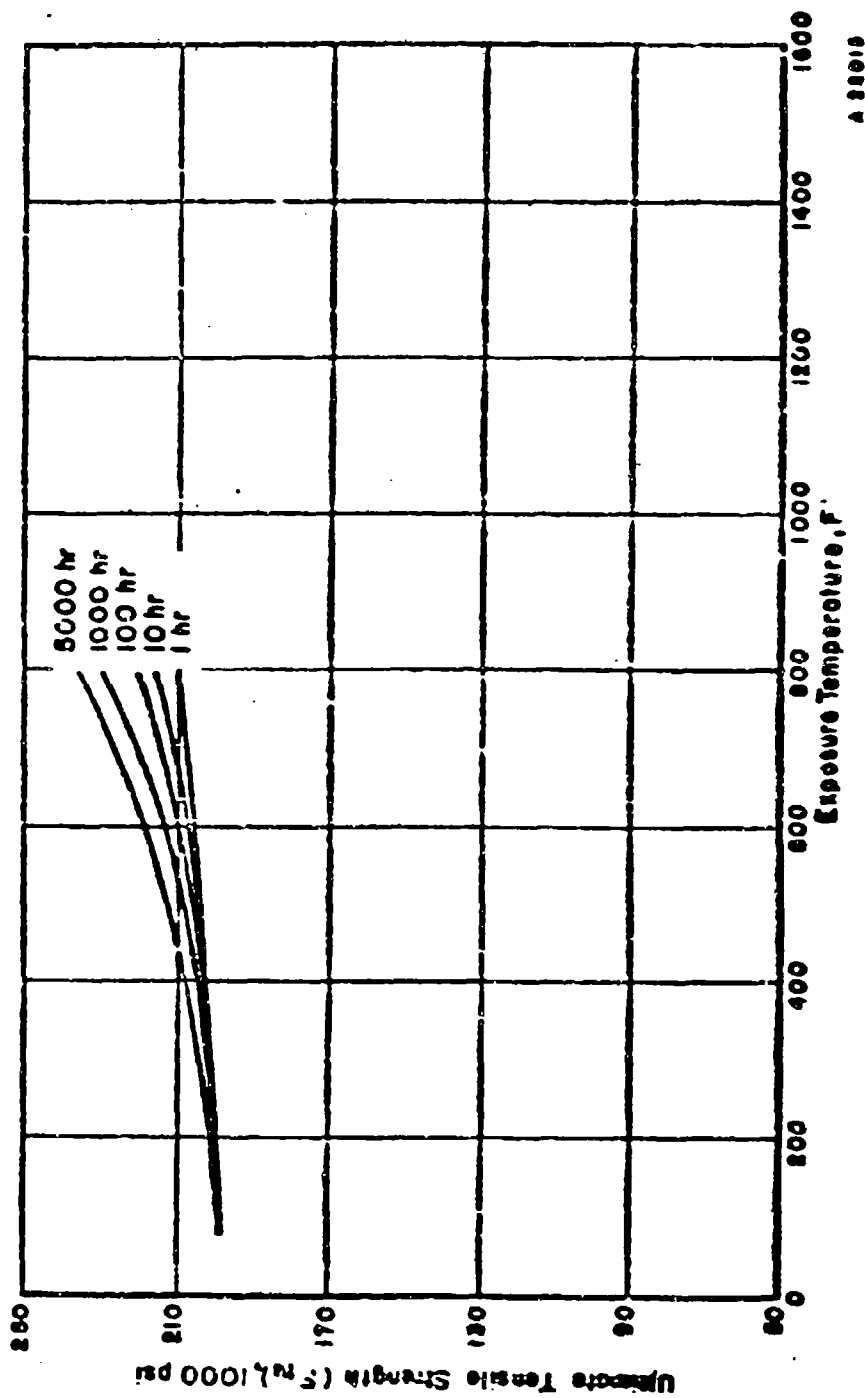


FIGURE 138. EFFECT OF EXPOSURE AT ELEVATED TEMPERATURE ON THE ROOM-TEMPERATURE TENSILE STRENGTH (F_u) OF 17-4PH STAINLESS STEEL

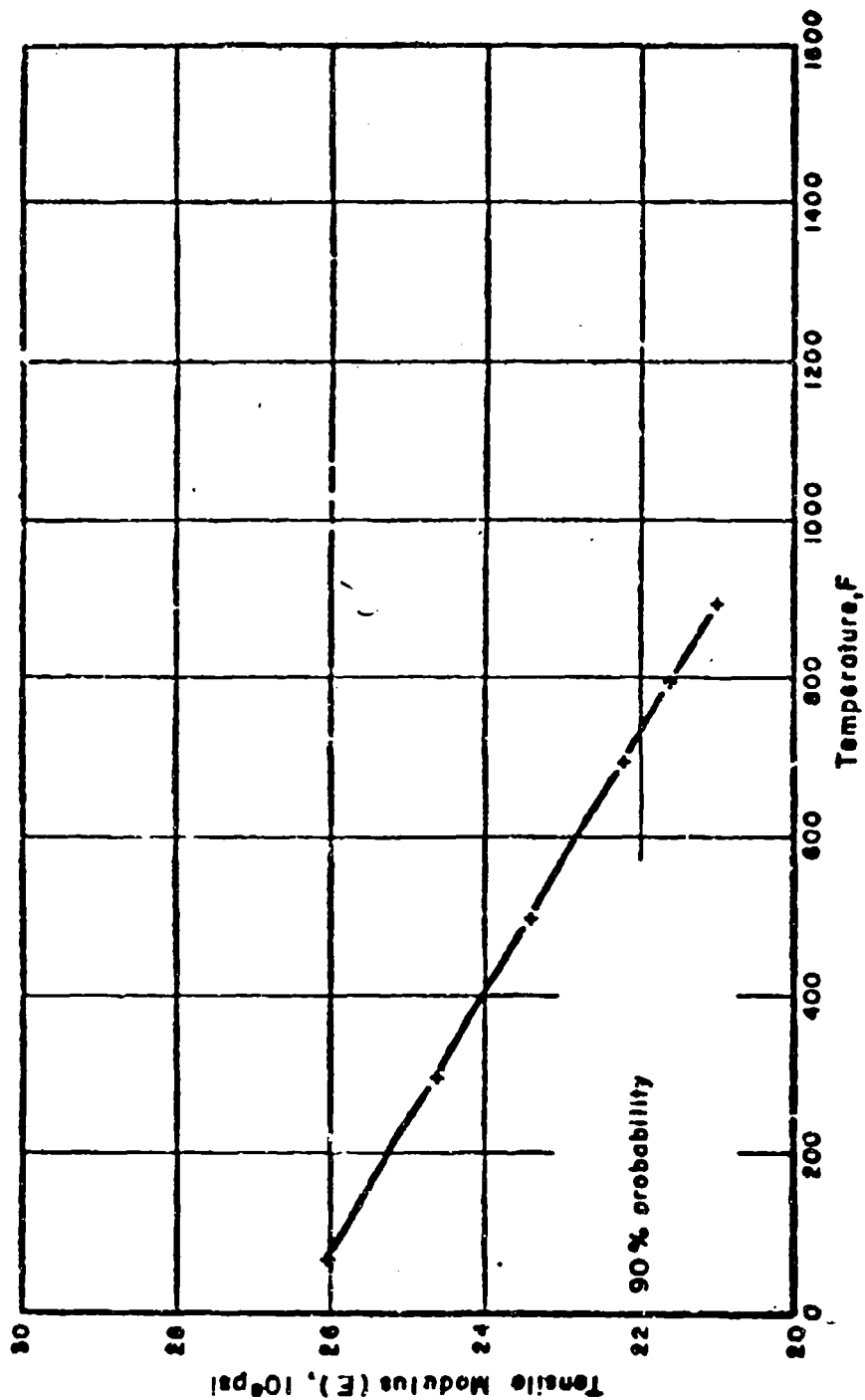


FIGURE 139. TENSILE MODULUS (E) OF 17-4PH STAINLESS STEEL FORGING
AT ELEVATED TEMPERATURE

Ref. 192.

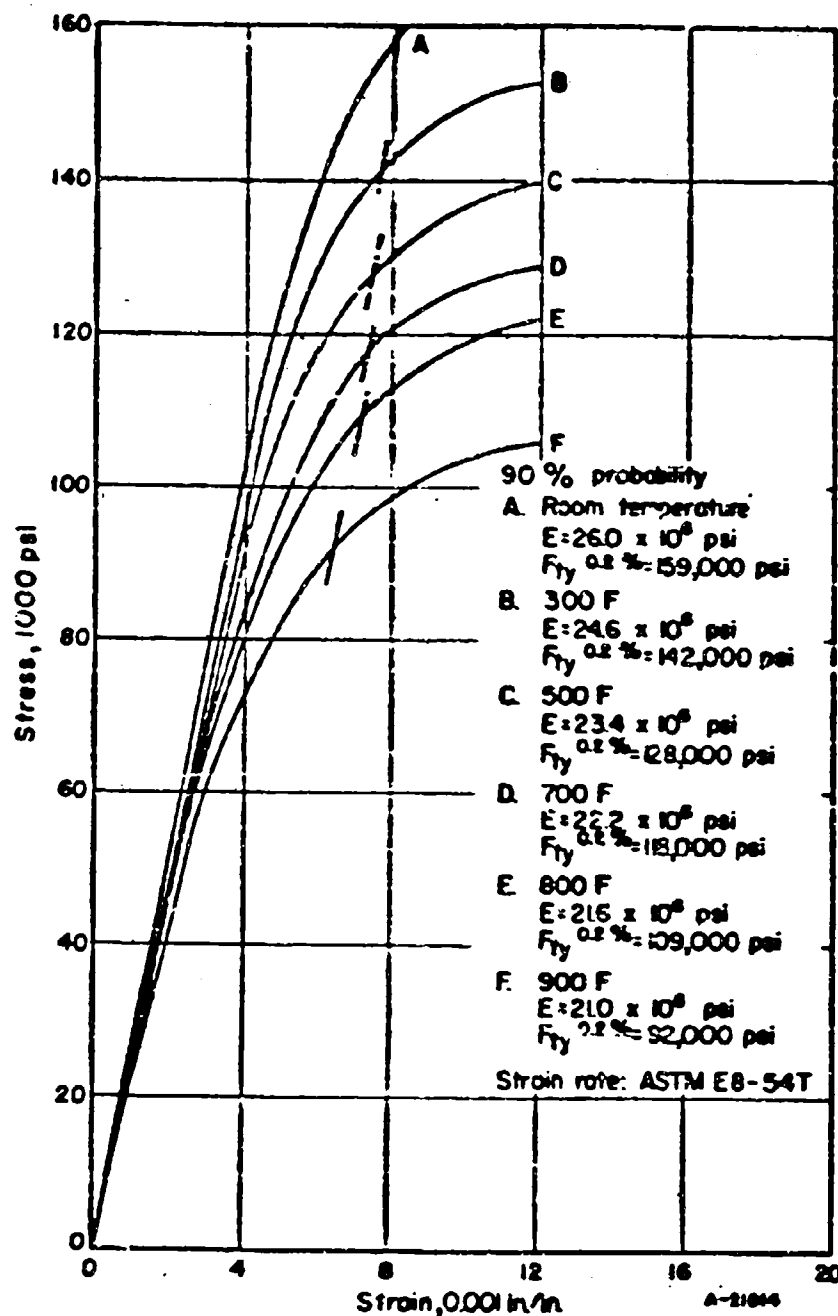


FIGURE 140. TENSILE STRESS-STRAIN CURVES FOR 17-4PH STAINLESS STEEL FORGING AT ROOM AND ELEVATED TEMPERATURE

Ref. 192.

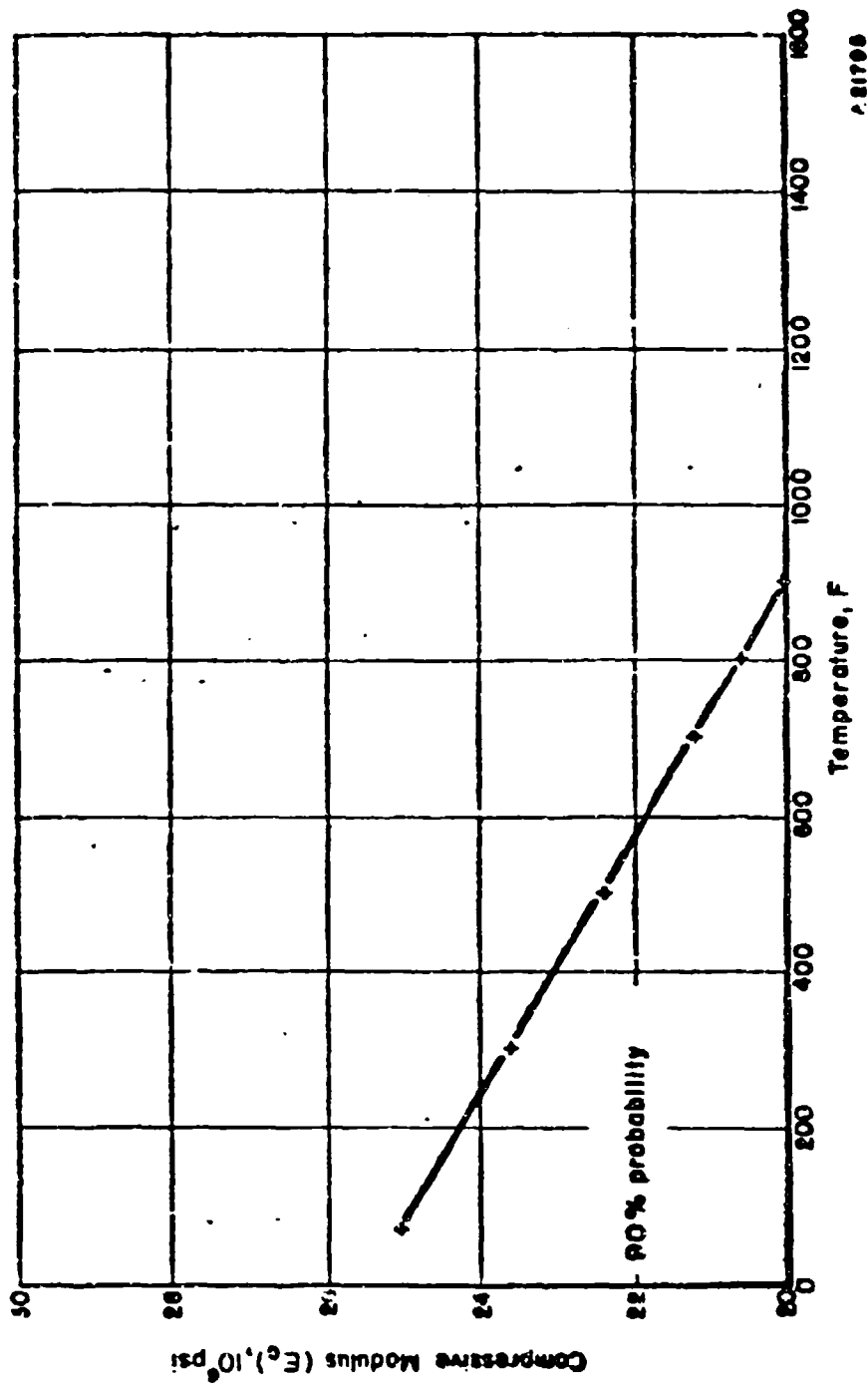


FIGURE 141. COMPRESSIVE MODULUS (E_c) OF 17-4PH STAINLESS STEEL
FORGING AT ELEVATED TEMPERATURE

Ref. 192.

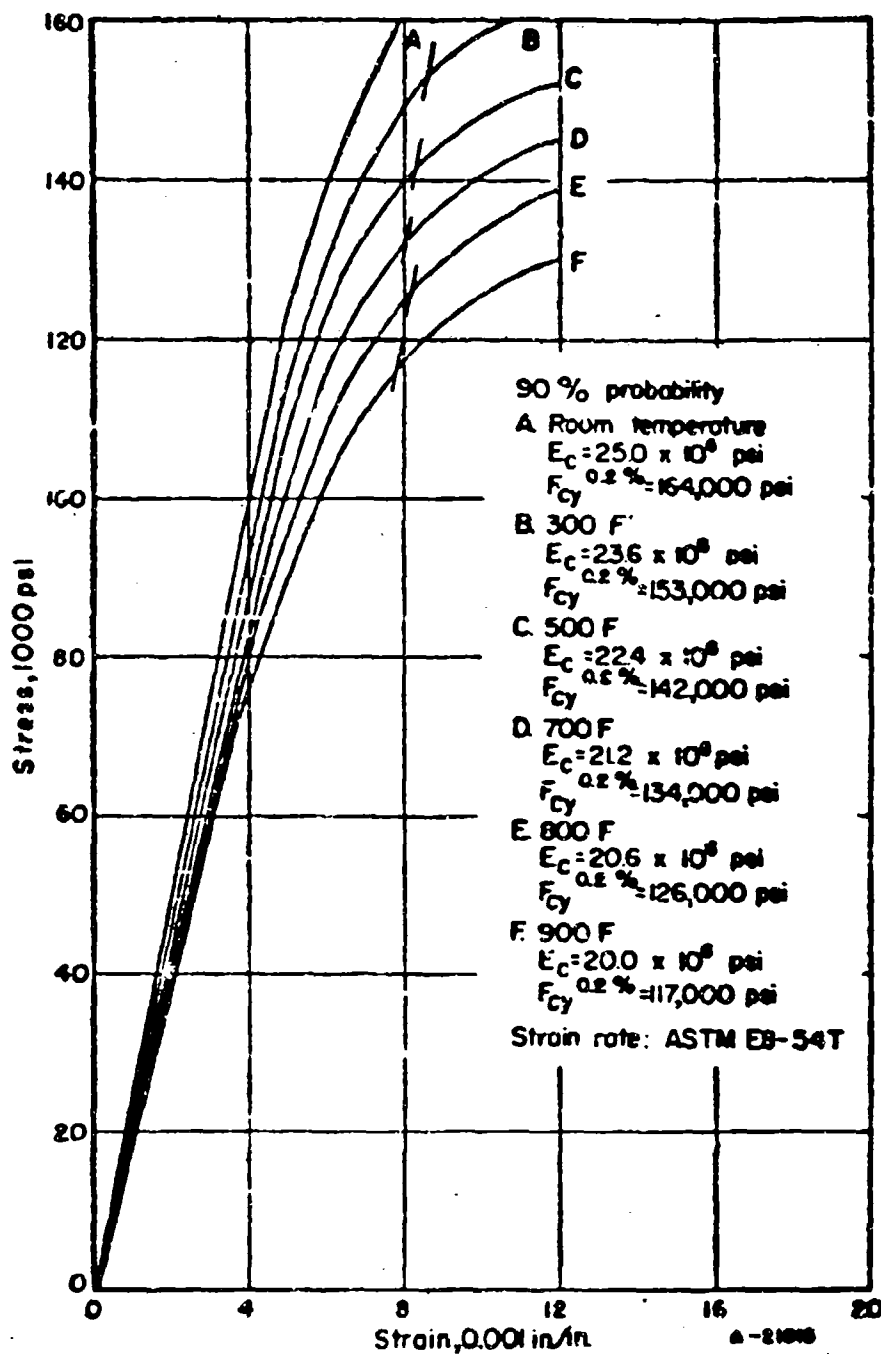


FIGURE 142. COMPRESSIVE STRESS-STRAIN CURVES FOR 17-4PH STAINLESS STEEL FORGING AT ROOM AND ELEVATED TEMPERATURE

Ref. 192.

19-9DL ALLOY
(AMS-5526B) (AMS-5527A)

Alloy 19-9DL is a chromium-nickel alloy that has a predominantly austenitic structure. The typical chemical composition is given in Table 8.

TABLE 8. TYPICAL CHEMICAL COMPOSITION OF 19-9DL HEAT-RESISTANT ALLOY (AMS-5526B) (AMS-5527A)

Element	Weight Per Cent
Carbon	0.30
Manganese	1.25
Silicon	0.55
Nickel	9.00
Chromium	19.00
Molybdenum	1.25
Tungsten	1.25
Columbium + tantalum	0.40
Titanium	0.20
Iron	Balance

The alloy 19-9DL is usually used in the annealed or stress-relieved condition at temperatures below approximately 1300 F. For service above approximately 1300 F, the alloy is solution treated and aged. Other conditions are useful for numerous applications. Table 9 gives the minimum mechanical properties of 19-9DL after solution heat treating at 1800 F \pm 25 F and air cooling.

TABLE 9. MINIMUM MECHANICAL PROPERTIES OF 19-9DL ALLOY (AMS-5526B)

Property	
Ultimate tensile (F_{tu})	95,000-120,000 psi
Tensile yield (F_{ty})	45,000 psi (minimum)
Elongation (e) in 2 inches	30 per cent (minimum)

Table 10 gives the minimum mechanical properties of 19-9DL after stress relieving at 1200 F \pm 25 F, and air cooling.

TABLE 10. MINIMUM MECHANICAL PROPERTIES OF
19-9DL ALLOY (AMS-5527A)

Property	
Ultimate tensile (F_{tu})	125,000 psi (minimum)
Tensile yield (F_{ty})	90,000 psi (minimum)
Elongation (e) in 2 inches	12 per cent (minimum)

The short-time, elevated-temperature properties of 19-9DL are shown in the following curves:

- (1) Tensile properties, Figures 143 through 176.

Although the effect of many conditions and heat treatments on the tensile strength of 19-9DL has been investigated, no information is available on other design properties.

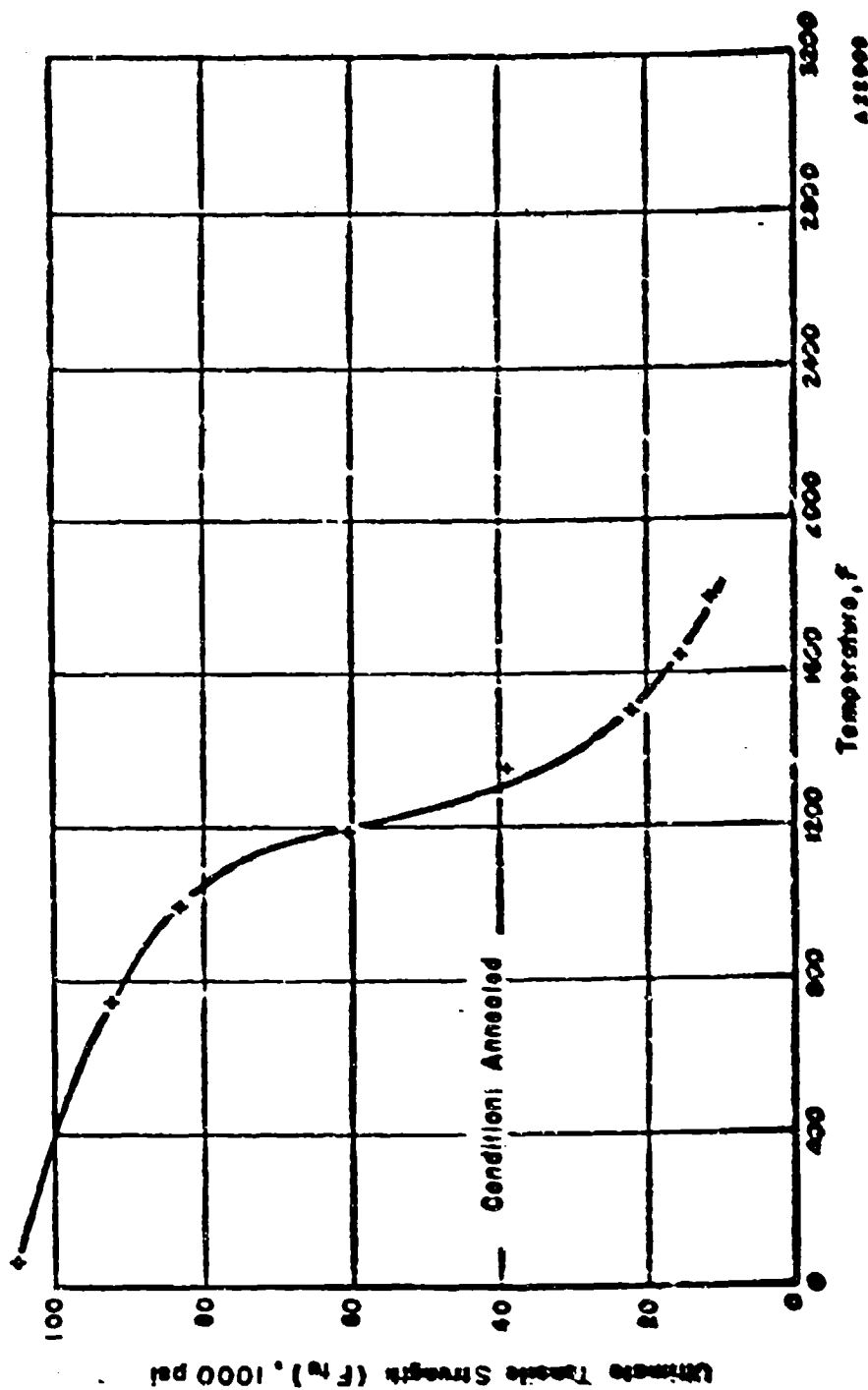


FIGURE 145. TENSILE STRENGTH (F_u) OF 19-9DL STAINLESS STEEL (ANNEALED) AT ELEVATED TEMPERATURE

Ref. 16.

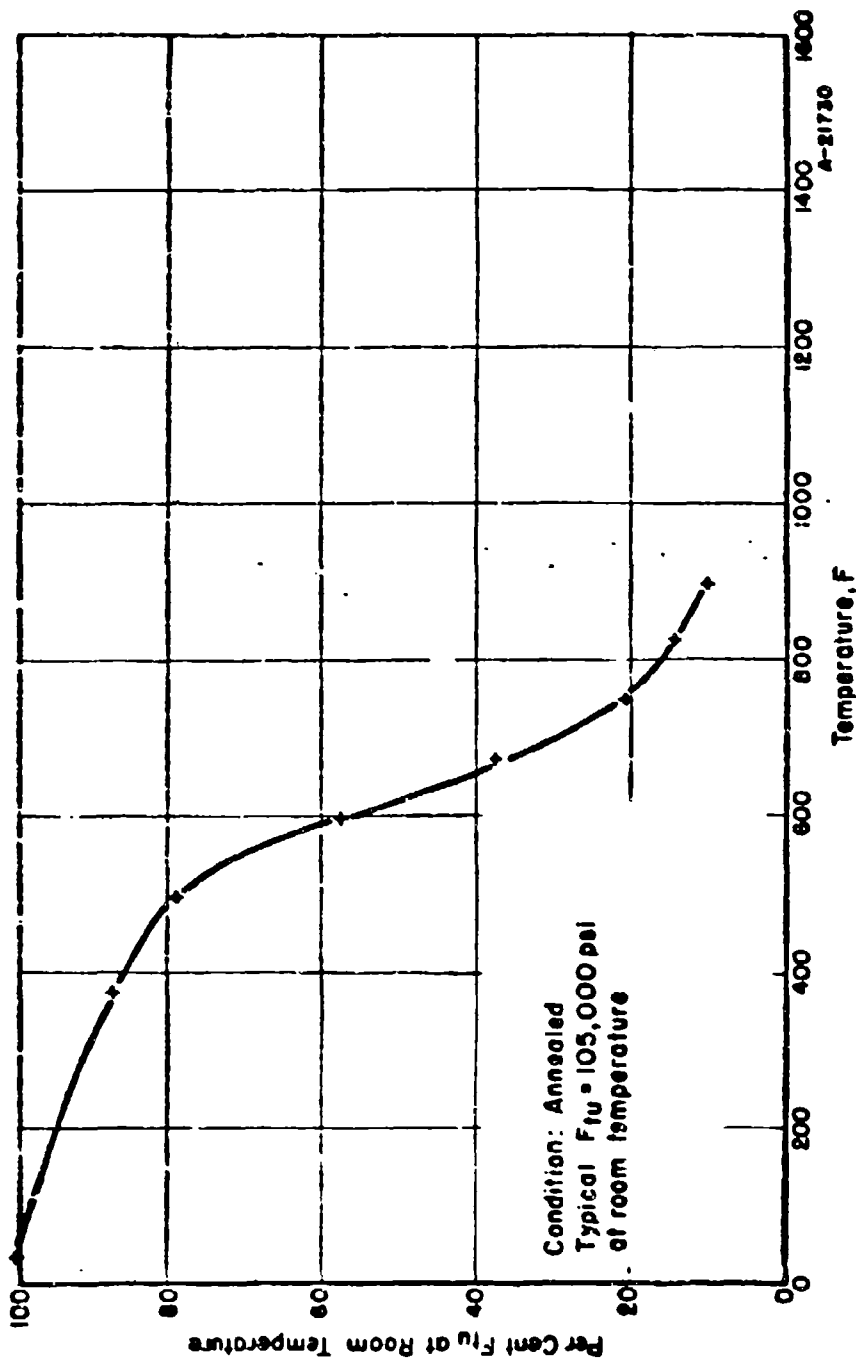


FIGURE 144. DESIGN CURVE FOR TENSILE STRENGTH (F_u) OF 19-9DL STAINLESS STEEL (ANNEALED) AT ELEVATED TEMPERATURE

Ref. 16.

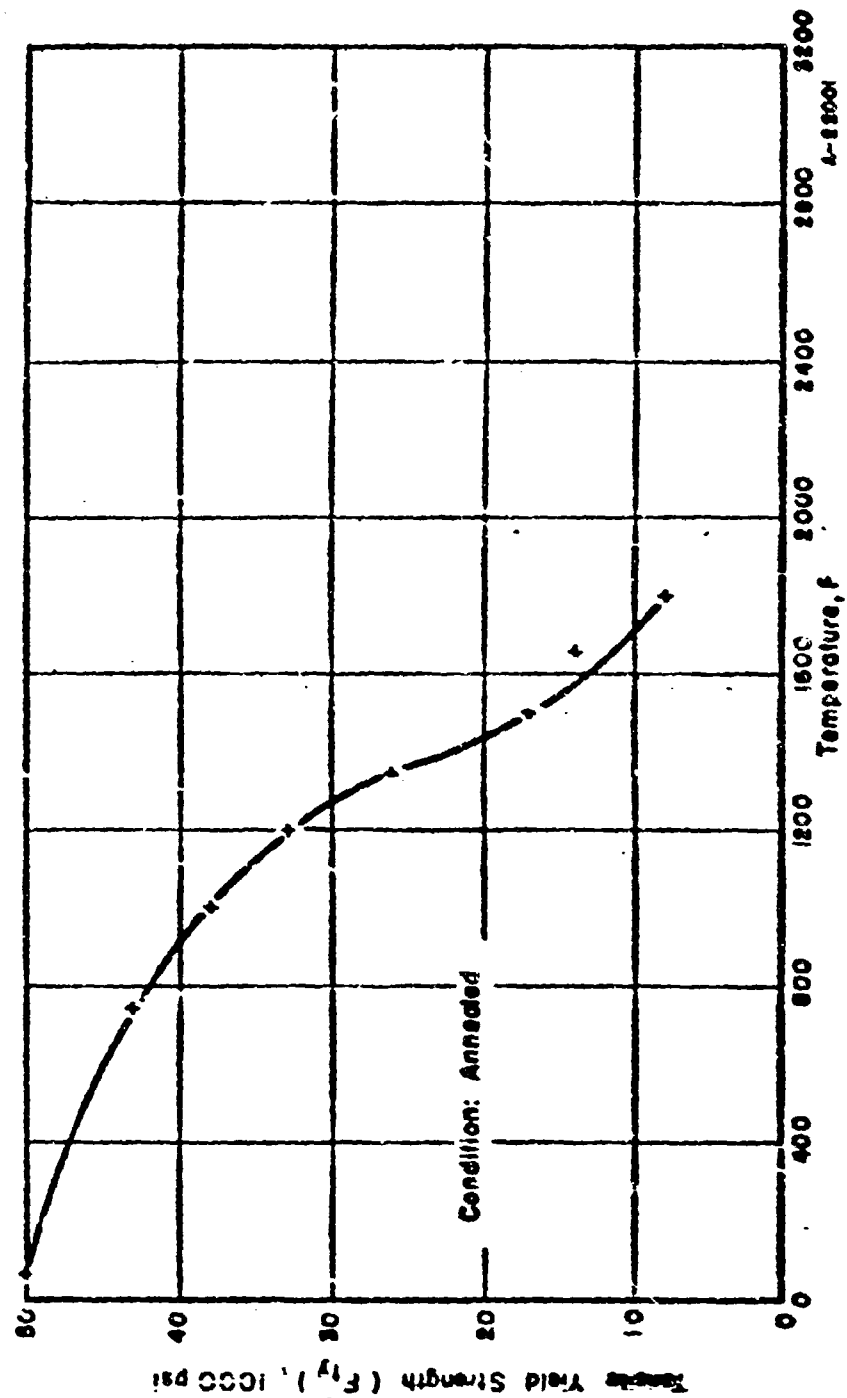


FIGURE 143. TENSILE YIELD STRENGTH (F_y) OF 19-9DL STAINLESS STEEL (ANNEALED) AT ELEVATED TEMPERATURE

Ref. 16.

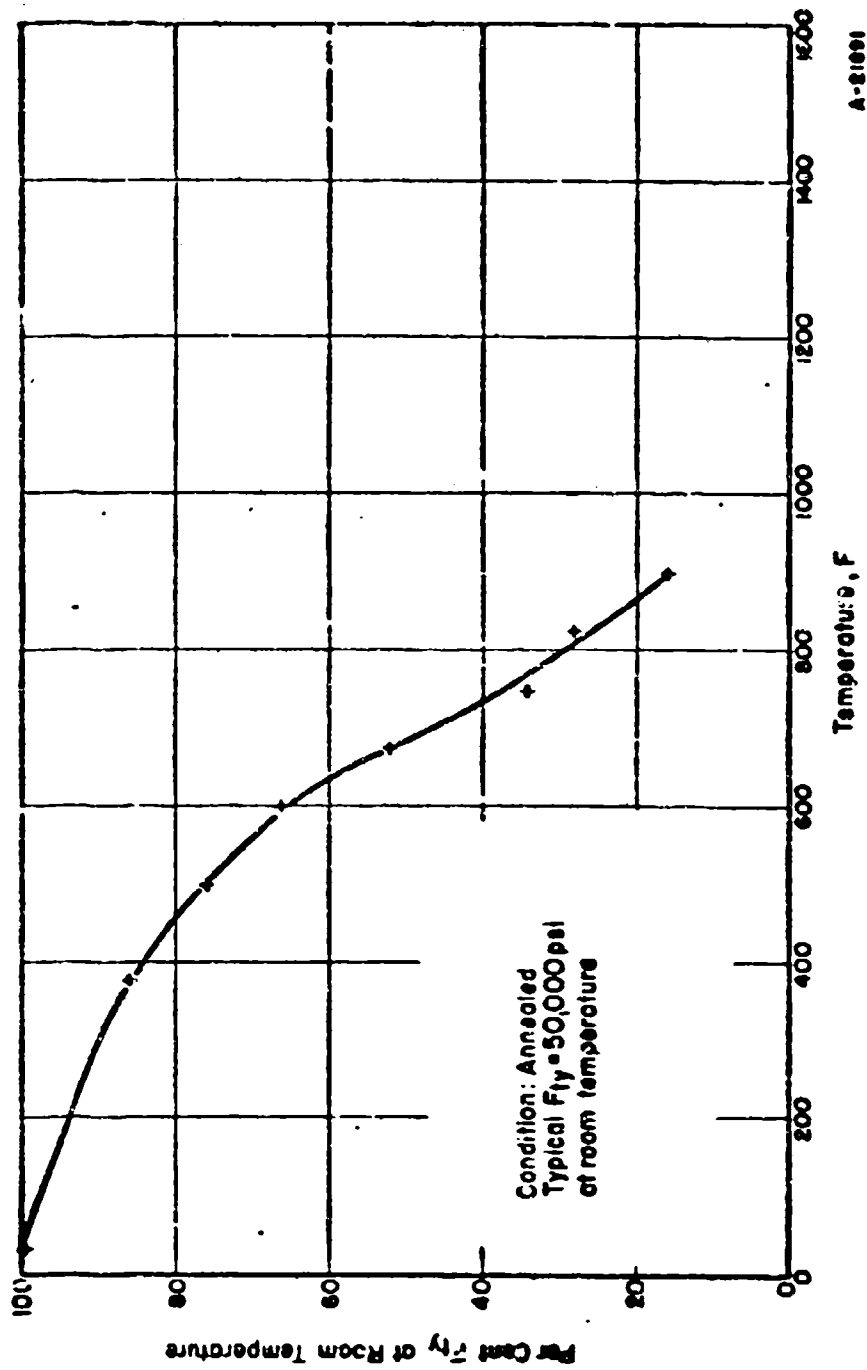


FIGURE 146. DESIGN CURVE FOR TENSILE YIELD STRENGTH (F_{ty}) OF 19-9DL STAINLESS STEEL

Ref. 16.

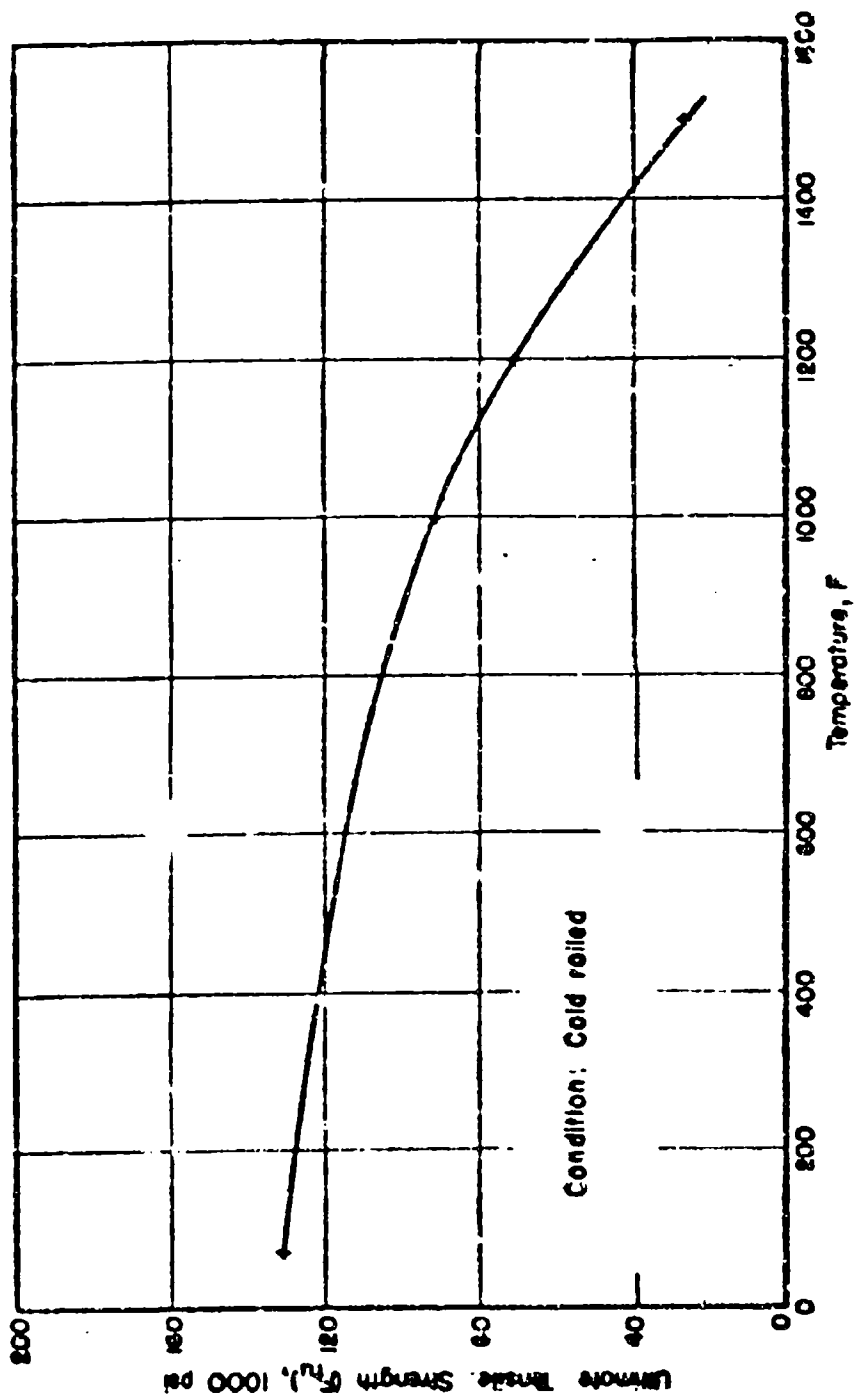


FIGURE 147. TENSILE STRENGTH (F_u) OF 19-9DL STAINLESS STEEL (COLD ROLLED) AT ELEVATED TEMPERATURE

Ref. 16.

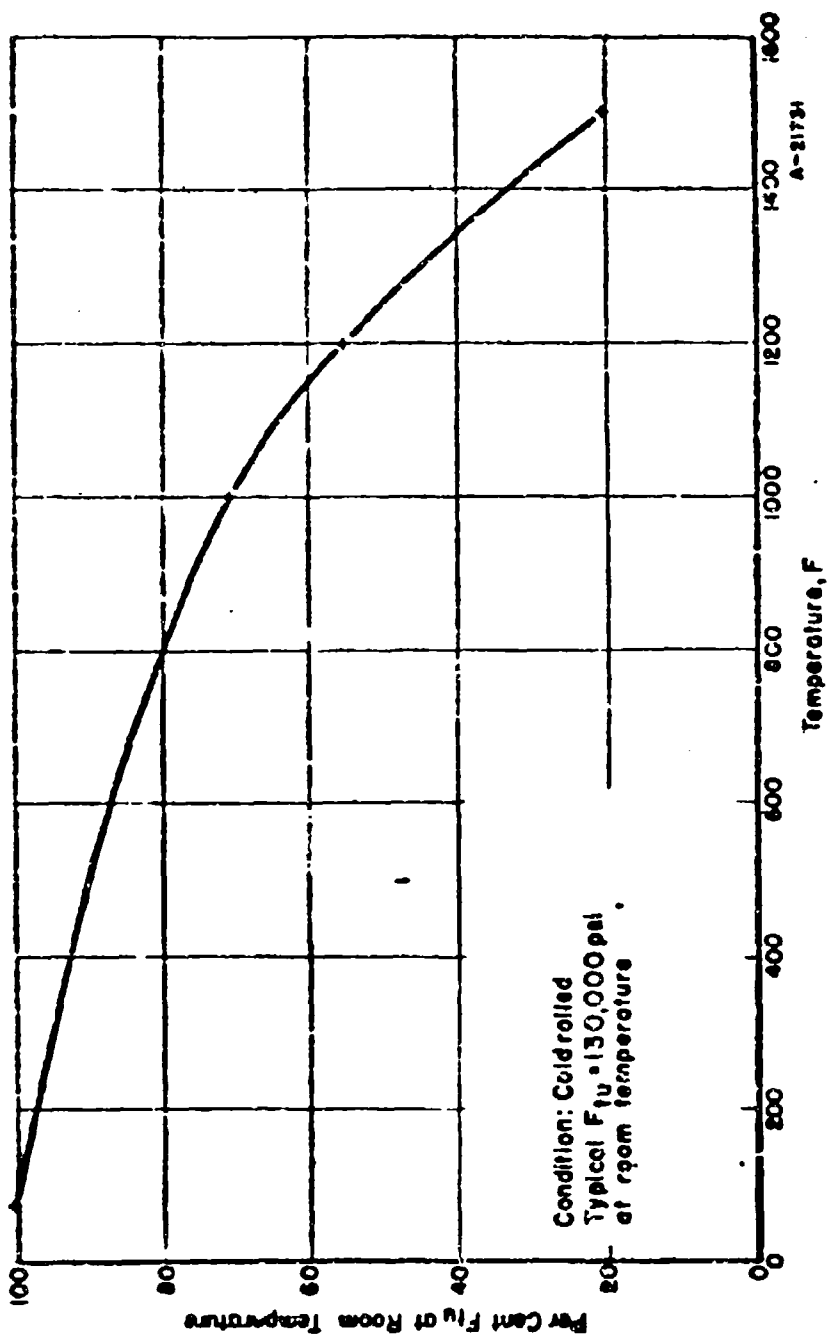


FIGURE 148. DESIGN CURVE FOR TENSILE STRENGTH (F_{10}) OF 19-9DL STAINLESS STEEL (COLD ROLLED) AT ELEVATED TEMPERATURE

Ref. 16.

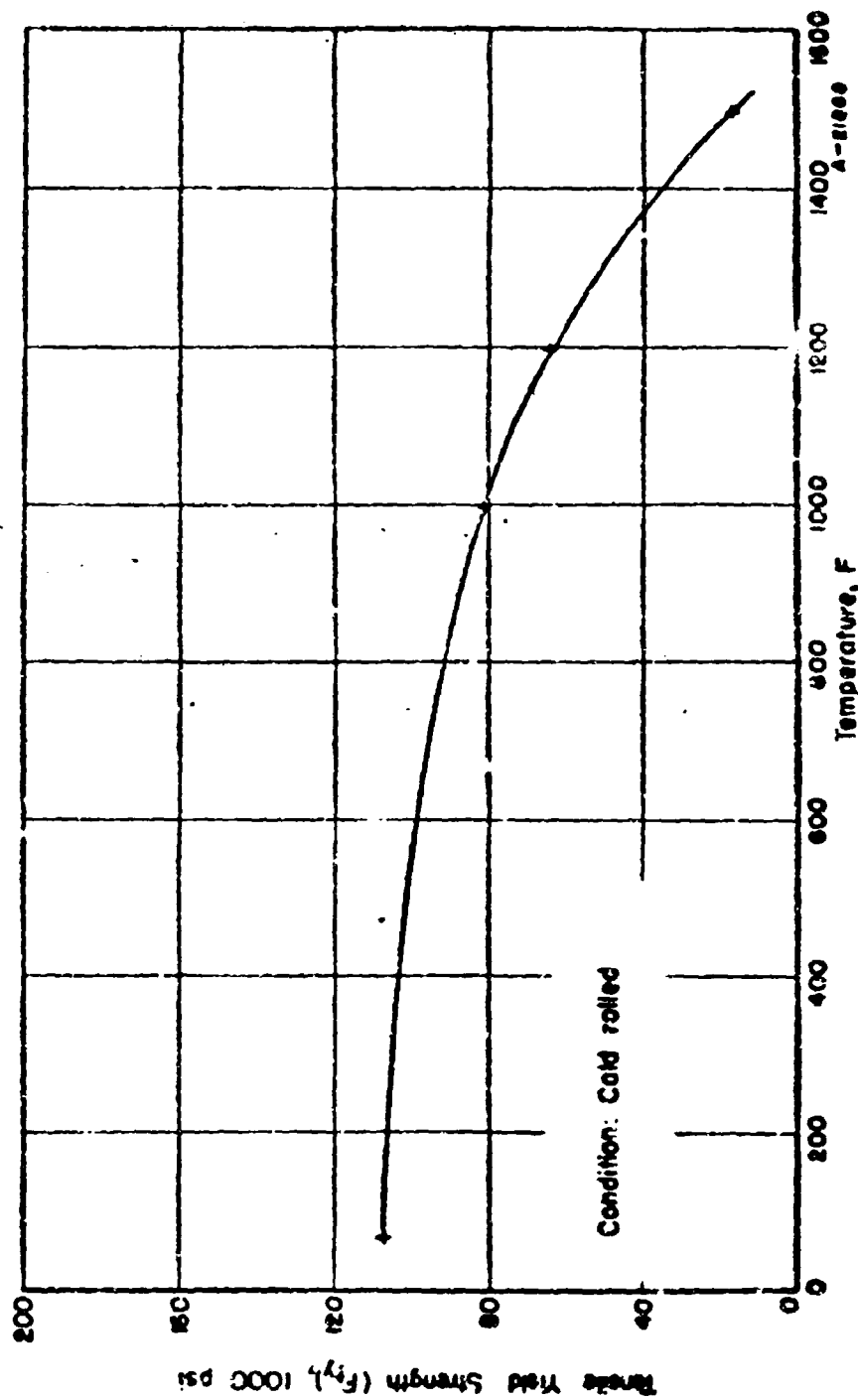


FIGURE 149. TENSILE YIELD STRENGTH (F_y) OF 19-9DL STAINLESS STEEL (COLD ROLLED) AT ELEVATED TEMPERATURE

Ref. 16.

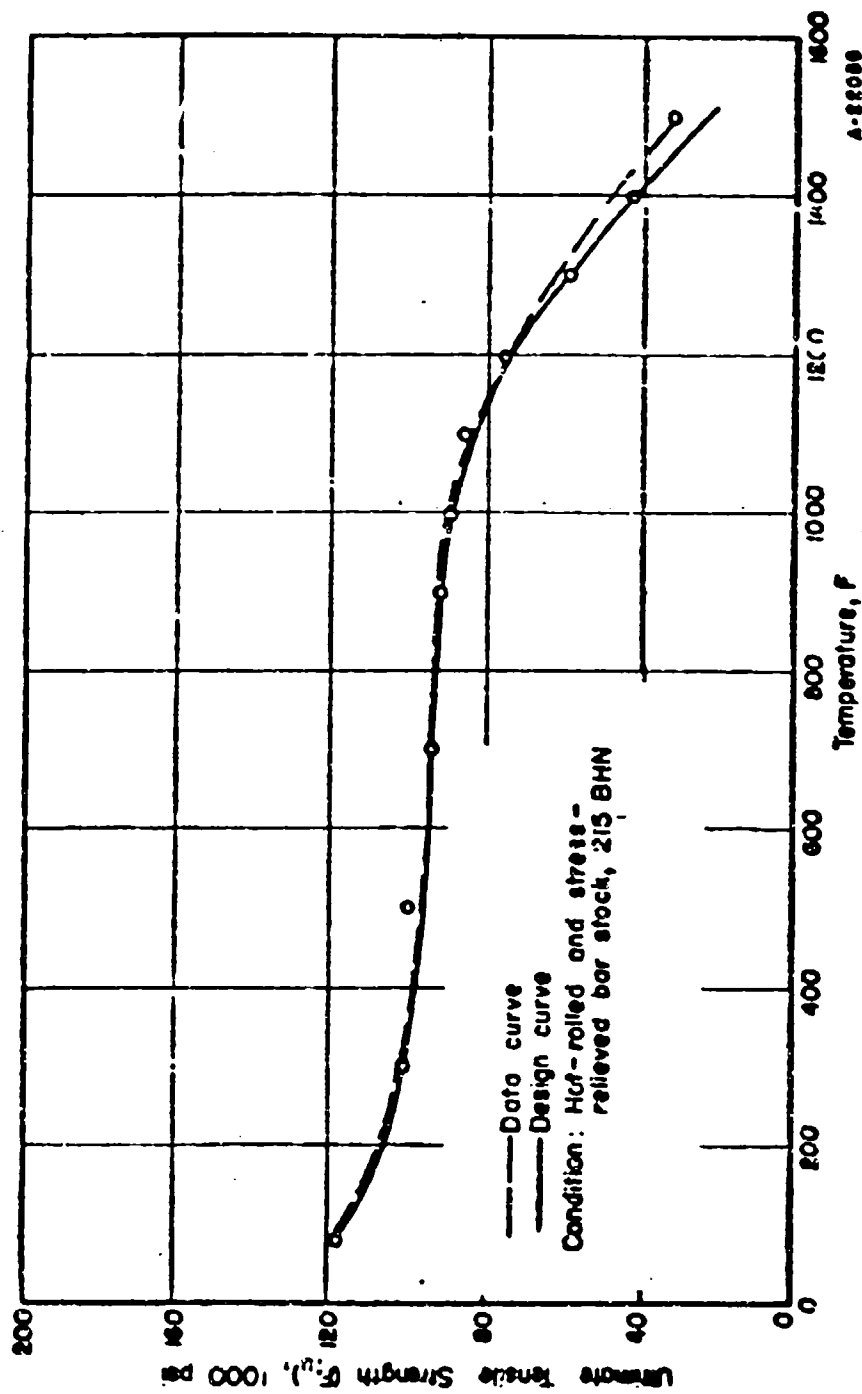


FIGURE 151. TENSILE STRENGTH (F_u) OF 19-9DL STAINLESS STEEL (HOT ROLLED AND STRESS RELIEVED) AT ELEVATED TEMPERATURE

Ref. 241.

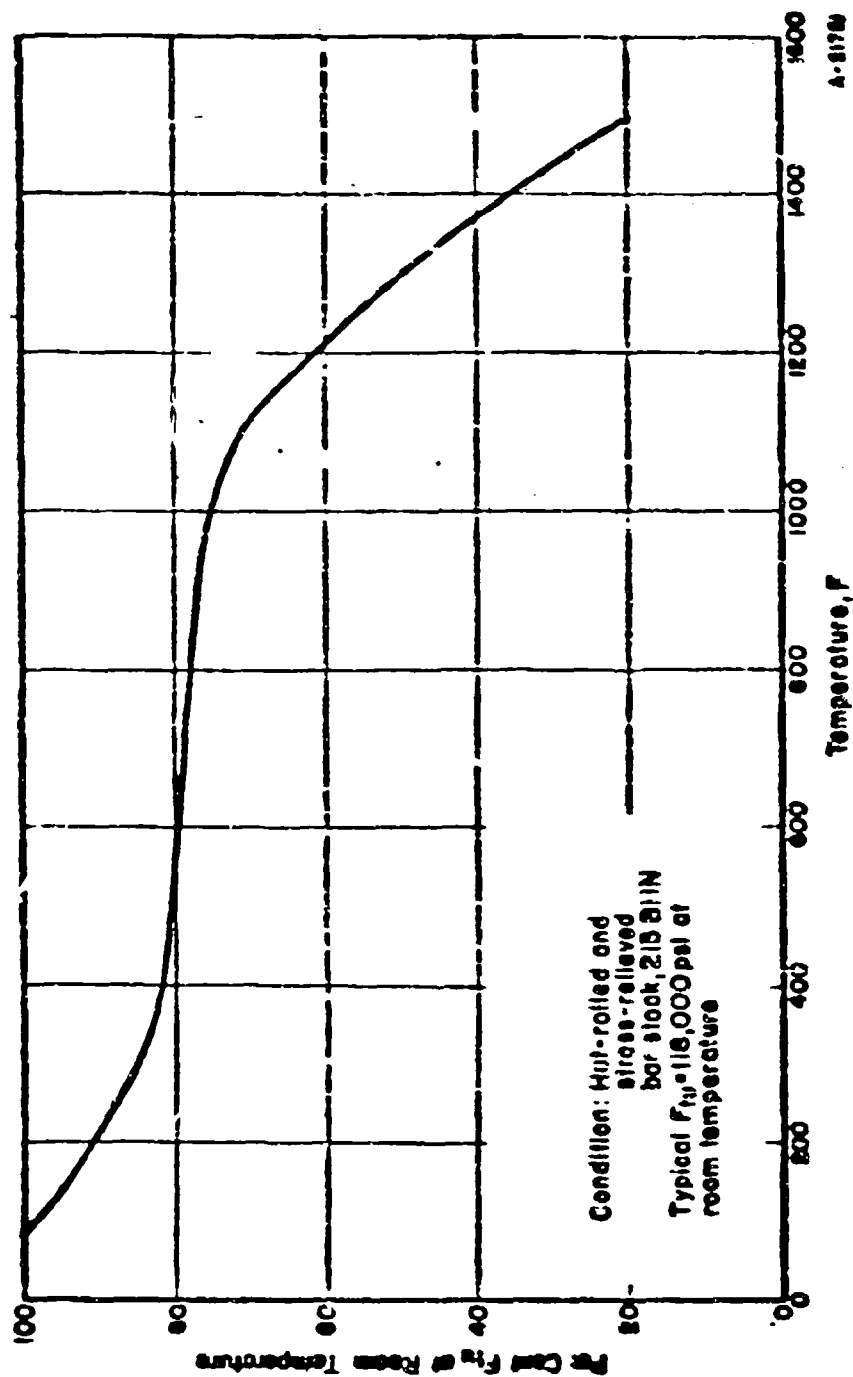


FIGURE 182. DESIGN CURVE FOR TENSILE STRENGTH (F_{T0}) OF 19-4DL STAINLESS STEEL (HOT ROLLED AND STRESS RELIEVED) AT ELEVATED TEMPERATURE

Ref. 241.

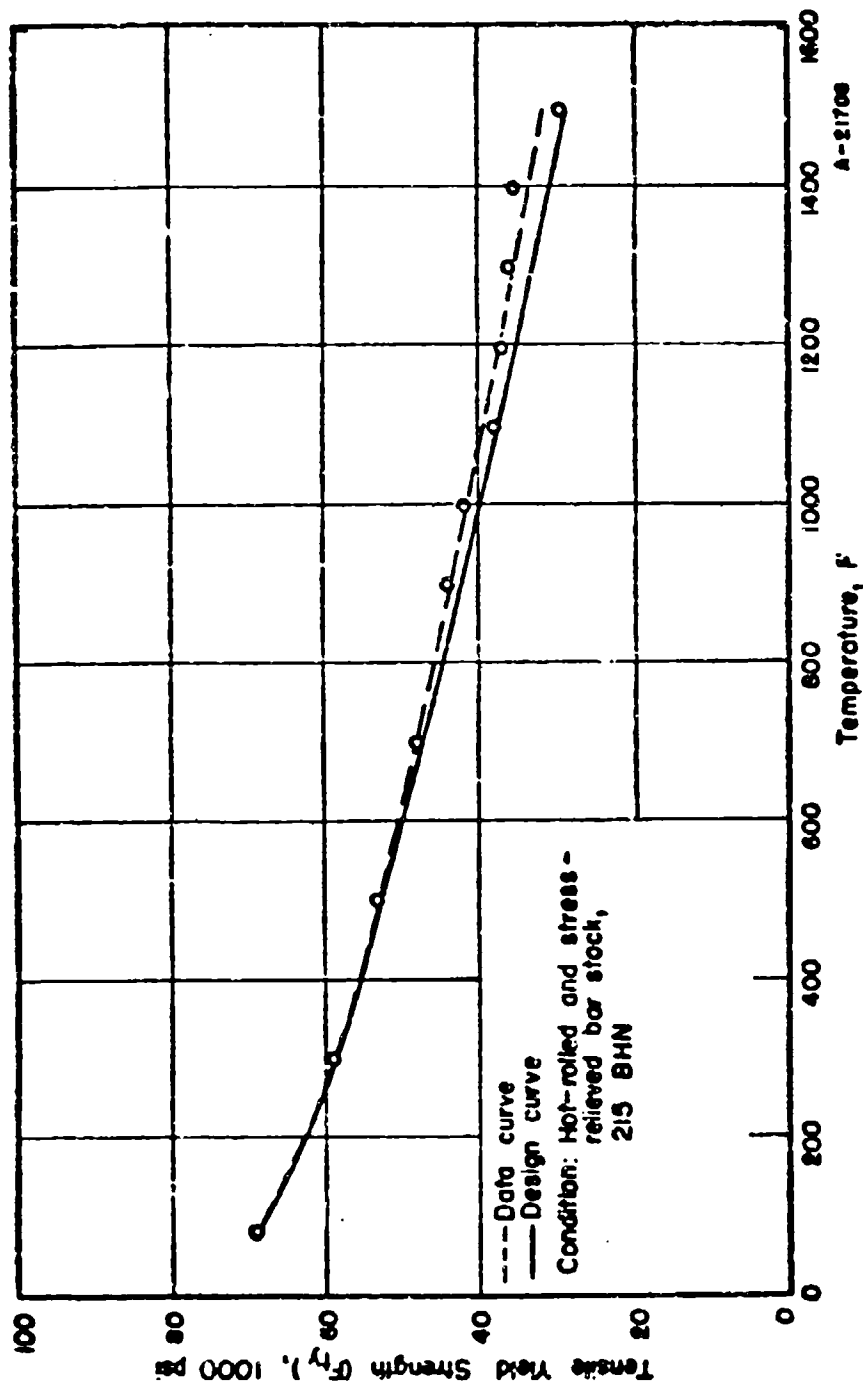


FIGURE 153. TENSILE YIELD STRENGTH (F_y) OF 19-9DL STAINLESS STEEL (HOT ROLLED AND STRESS RELIEVED) AT ELEVATED TEMPERATURE

Ref. 241.

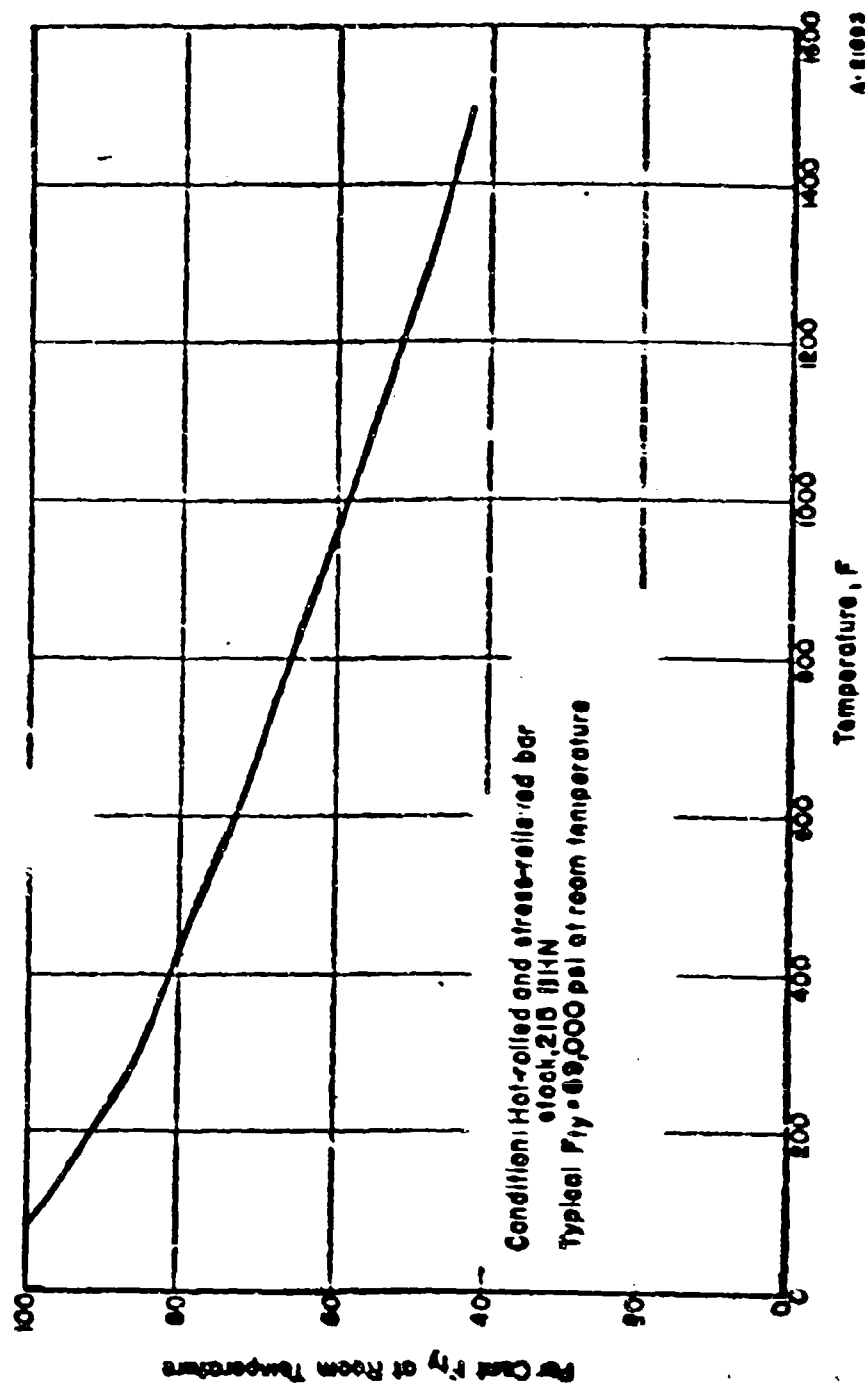


FIGURE 154. DESIGN CURVE FOR TENSILE YIELD STRENGTH (F_y) OF 19-9D1 STAINLESS STEEL (HOT ROLLED AND STRESS RELIEVED) AT ELEVATED TEMPERATURE
 Ref. 241.

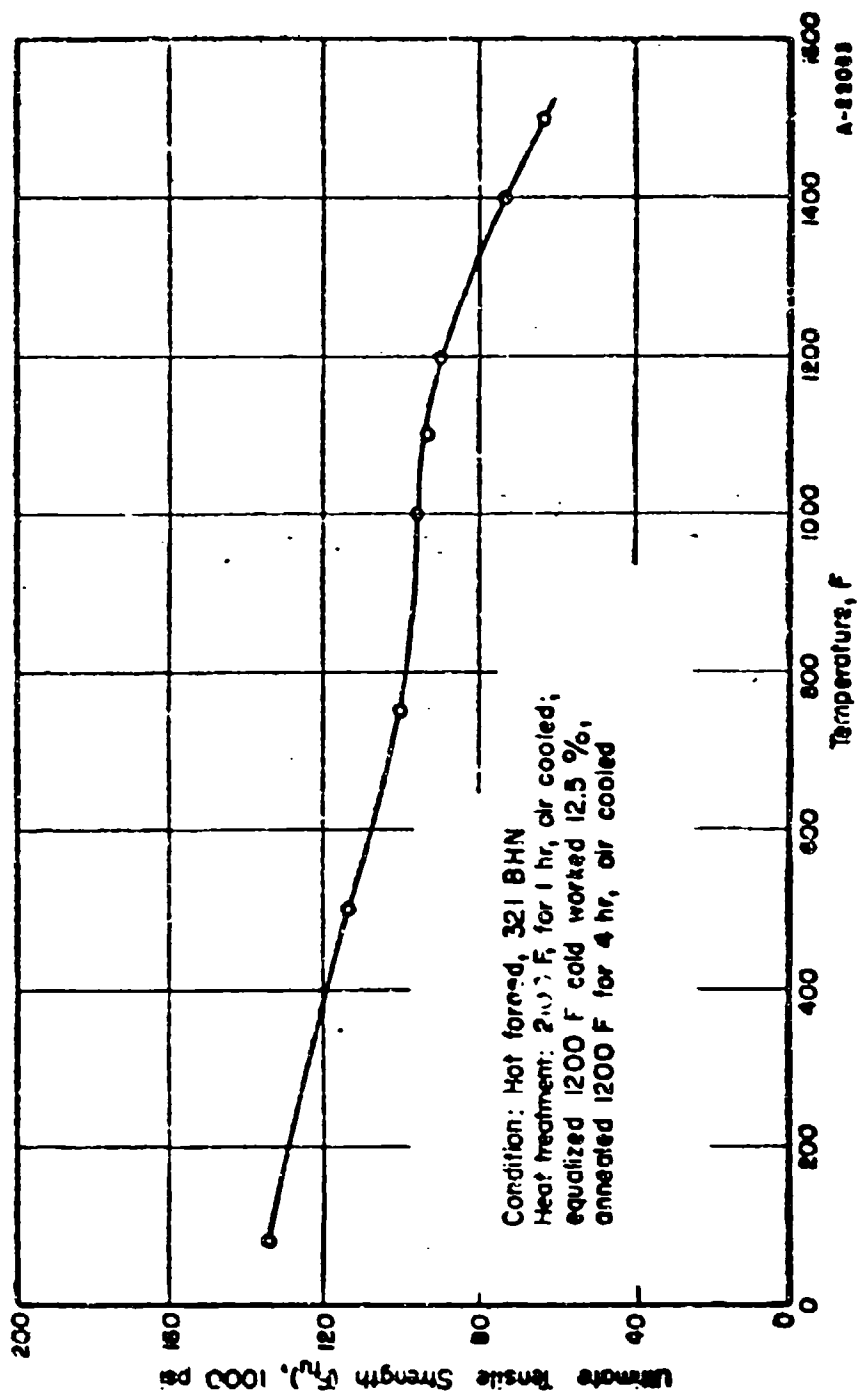


FIGURE 195. TENSILE STRENGTH (F_u) OF 19-9DL STAINLESS STEEL (HOT FORGED) AT ELEVATED TEMPERATURE

Ref. 29, Data Sheet 4.

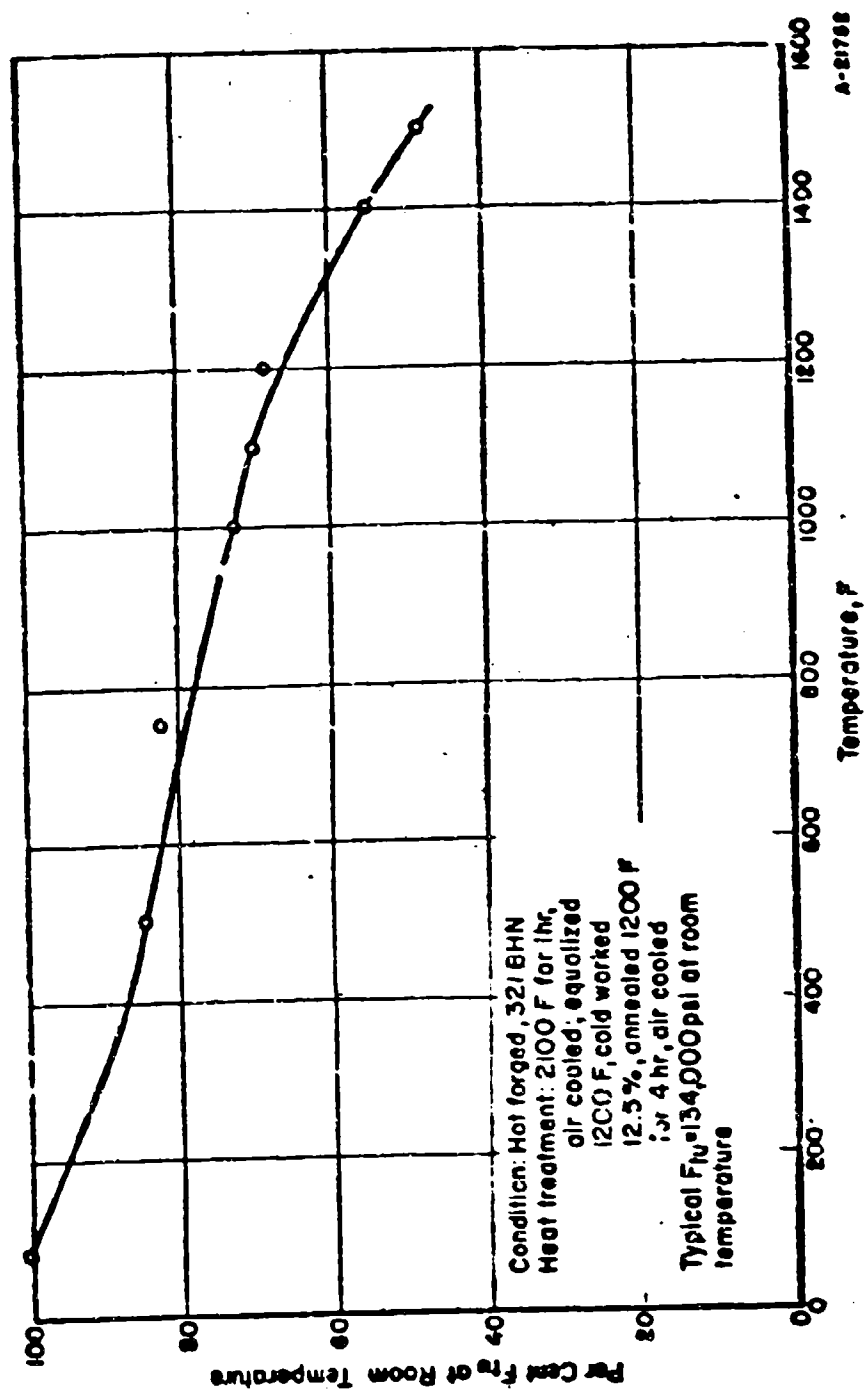


FIGURE 196. DESIGN CURVE FOR TENSILE STRENGTH (F_T) OF 19-9DL STAINLESS STEEL (HOT FORGED) AT ELEVATED TEMPERATURE

Ref. 20, Data Sheet 4.

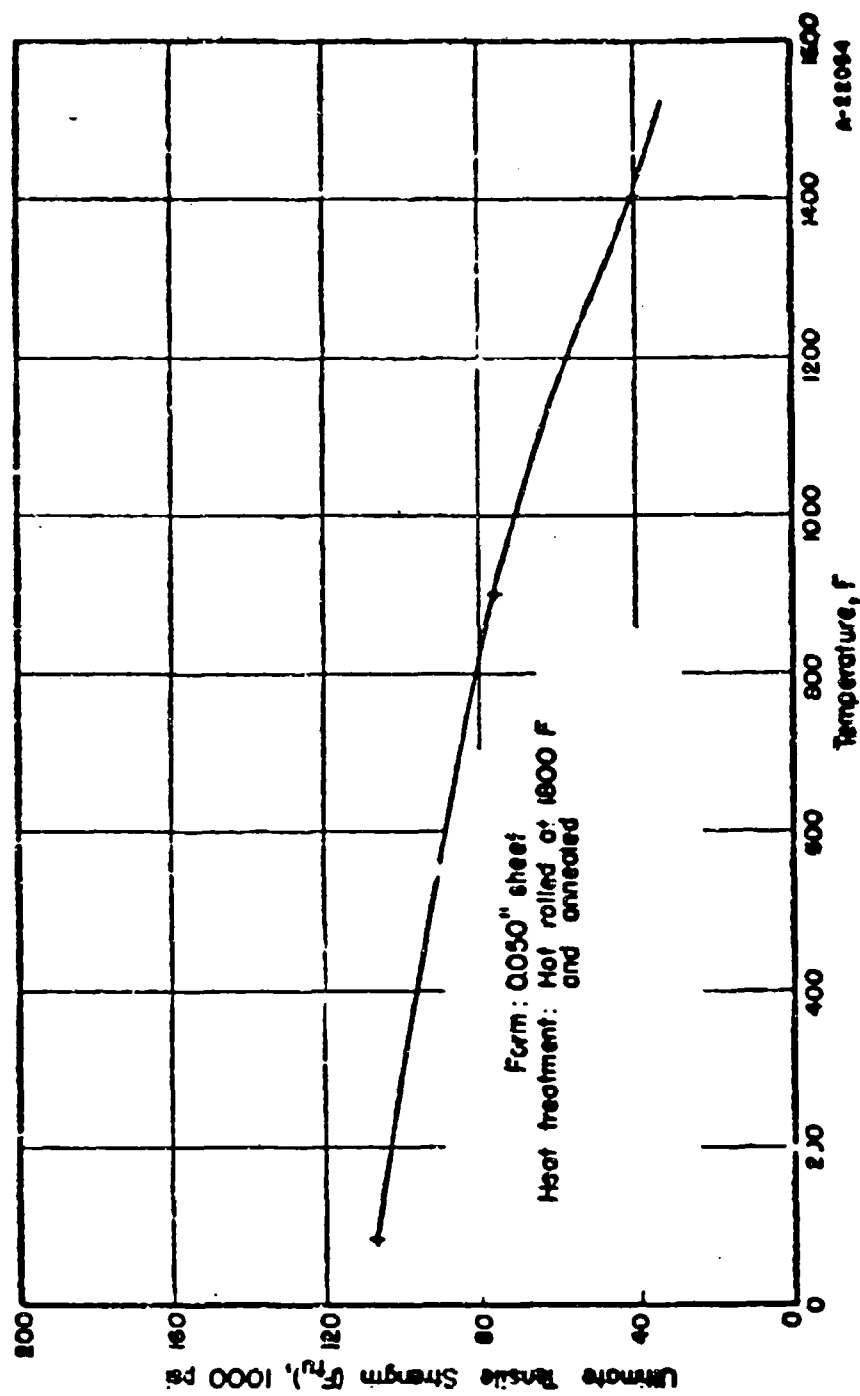


FIGURE 147. TENSILE STRENGTH (F_u) OF 19-9DL STAINLESS STEEL (HOT ROLLED) AT ELEVATED TEMPERATURE

Ref. 29, Data Sheet 23.

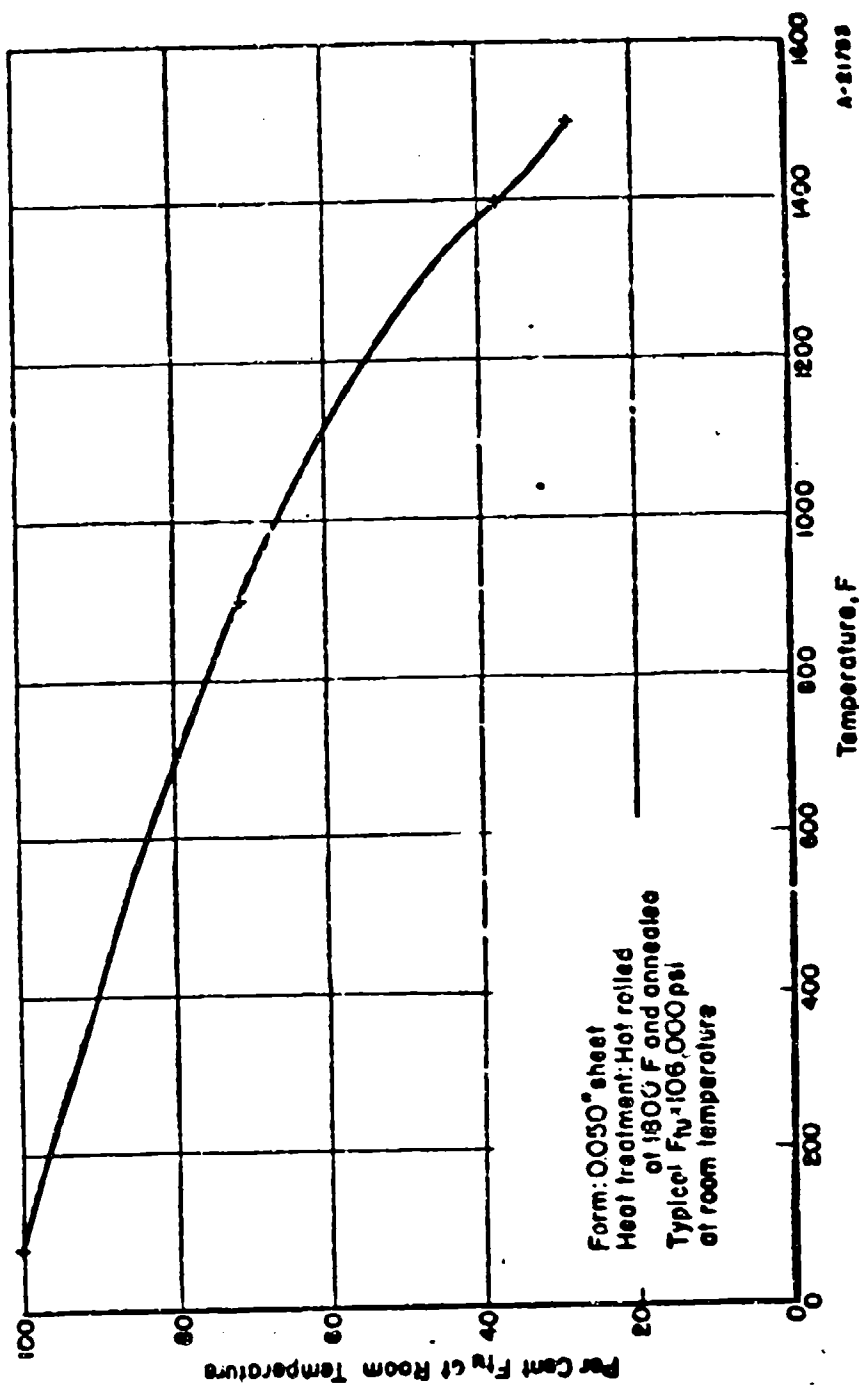


FIGURE 158. DESIGN CURVE FOR TENSILE STRENGTH (F_u) OF 19-9DL STAINLESS STEEL (HOT ROLLED) AT ELEVATED TEMPERATURE

Ref. 29, Data Sheet 23.

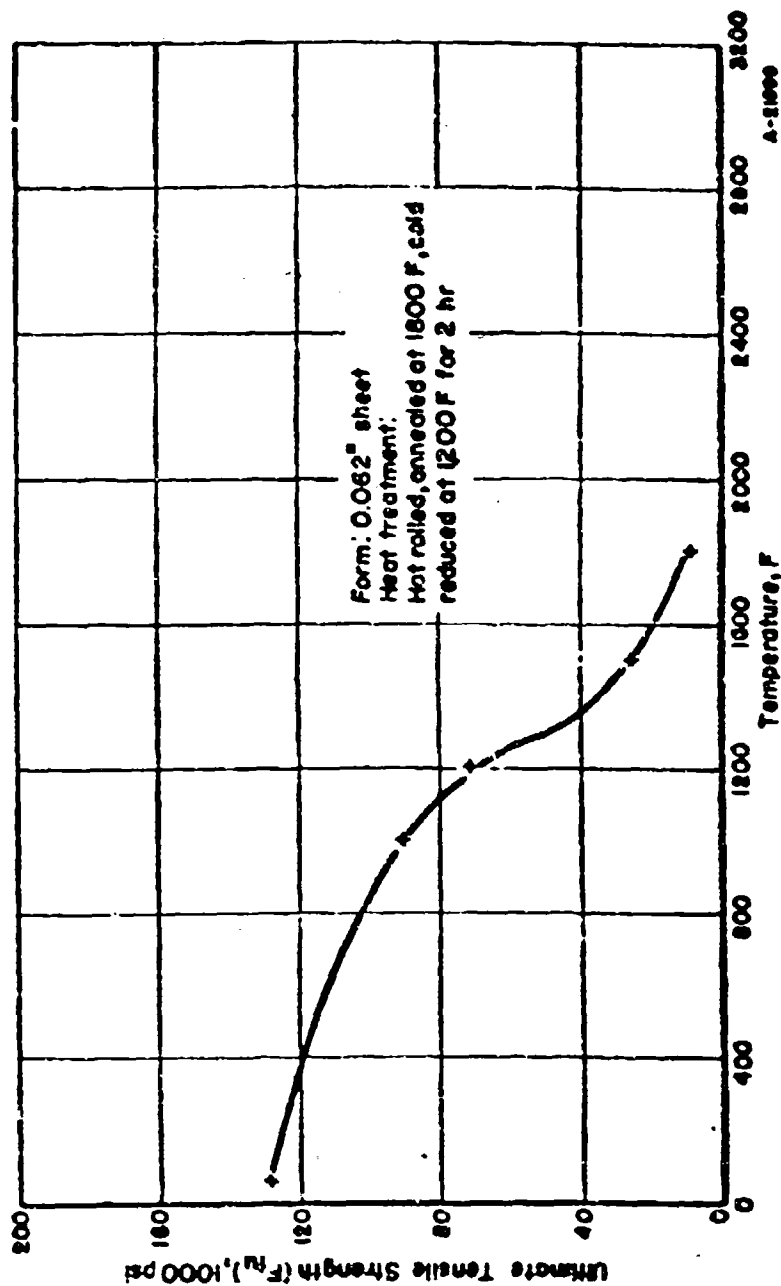


FIGURE 159. TENSILE STRENGTH (F_u) OF 19-9DL STAINLESS STEEL (HOT ROLLED) AT ELEVATED TEMPERATURE

Ref. 29, Data Sheet 22.

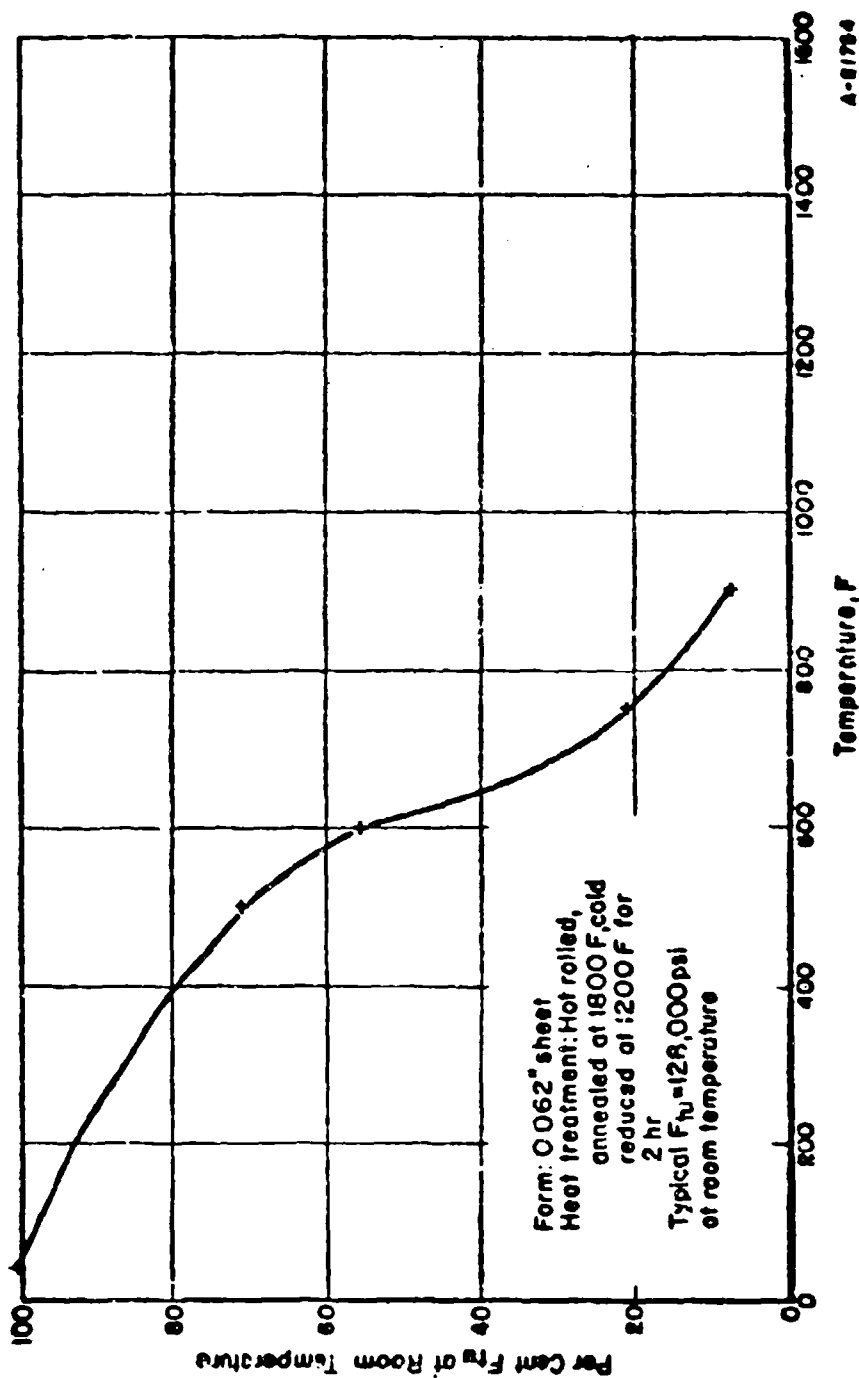


FIGURE 160. DESIGN CURVE FOR TENSILE STRENGTH (F_u) OF 19-4DL STAINLESS STEEL
(HOT ROLLED) AT ELEVATED TEMPERATURE
Ref. 29, Data Sheet 22.

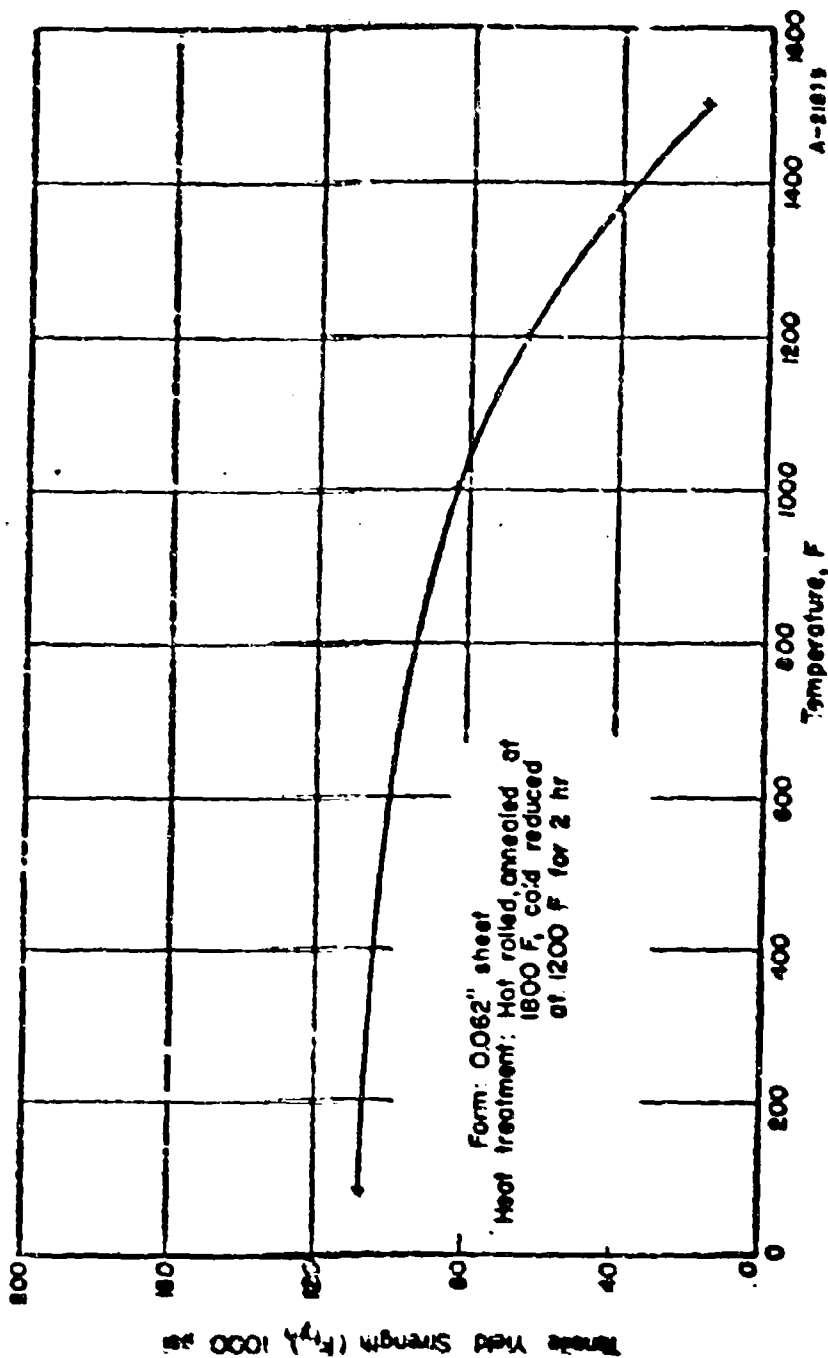


FIGURE 161. TENSILE YIELD STRENGTH (F_y) OF 19-9DL STAINLESS STEEL (HOT ROLLED) AT ELEVATED TEMPERATURE

Ref. 29, Data Sheet 22.

- (25) Ross, A. O., "Determination of Boundary-Layer Transition Reynolds Numbers by Surface-Temperature Measurements of a 10-Degree Cone in Various NACA Supersonic Wind Tunnels", NACA TN 3020, October 1953, 26 pages.
- (26) Miller, R. F., and Heger, J. J., "The Strength of Wrought Steels at Elevated Temperatures", ASTM-ASME Joint Committee, ASTM Special Publication No. 160 (1950).
- (27) Simmons, W. F., and Cross, H. C., "The Elevated Temperature Properties of Stainless Steels", ASTM-ASME Joint Committee ASTM Special Publication No. 124 (1952).
- (28) Simmons, W. F., and Cross, H. C., "The Elevated Temperature Properties of Chromium-Molybdenum Steels", ASTM-ASME Joint Committee, ASTM Special Publication No. 151 (1953).
- (29) Simmons, W. F., and Cross, H. C., "The Elevated Temperature Properties of Selected Super-Strength Alloys", ASTM-ASME Joint Committee, ASTM Special Publication No. 160 (1954).
- (30) "Product Data Bulletin", Armco Steel Corporation, Development Engineering Dept., Middletown, Ohio (1952).
- (31) Larson, F. R., and Miller, J., "A Time-Temperature Relationship for Rupture and Creep Stresses", ASME Transactions, Vol 74, No. 5, July 1952, pages 765-775.
- (32) Craighead, C. M., Grube, K. P., Eastwood, L. W., and Lorig, C. H. (Battelle Memorial Institute), "The Effects of Temperature on the Mechanical Properties of Magnesium Alloys", Project Rand, Rand Corporation, R-146 (October, 1949).
- (33) Guarnieri, G. J., and Salvaggi, J., "Limiting High Temperature Creep and Rupture Stresses on Sheet Alloys for Jet Applications", Cornell Aeronautical Laboratory, T. M. Cal.-39 (Project Squad, USN-USAf) (September, 1951).
- (34) Flanagan, Ieosen, and Dorn (University of California), "Study of Forming Properties of Aluminum Alloy Sheet at Elevated Temperatures - Part XII: Stress Rupture and Creep Tests", Wright-Patterson Air Force Base Report No. W185 (March, 1945), Report N. W215 (June, 1945).
- (35) Dorn, J. E., and Tiez, T. E. (University of California), "Creep and Stress-Rupture Investigations on Some Aluminum Alloy Sheet Metals" (November, 1947). (See Reference 36.)

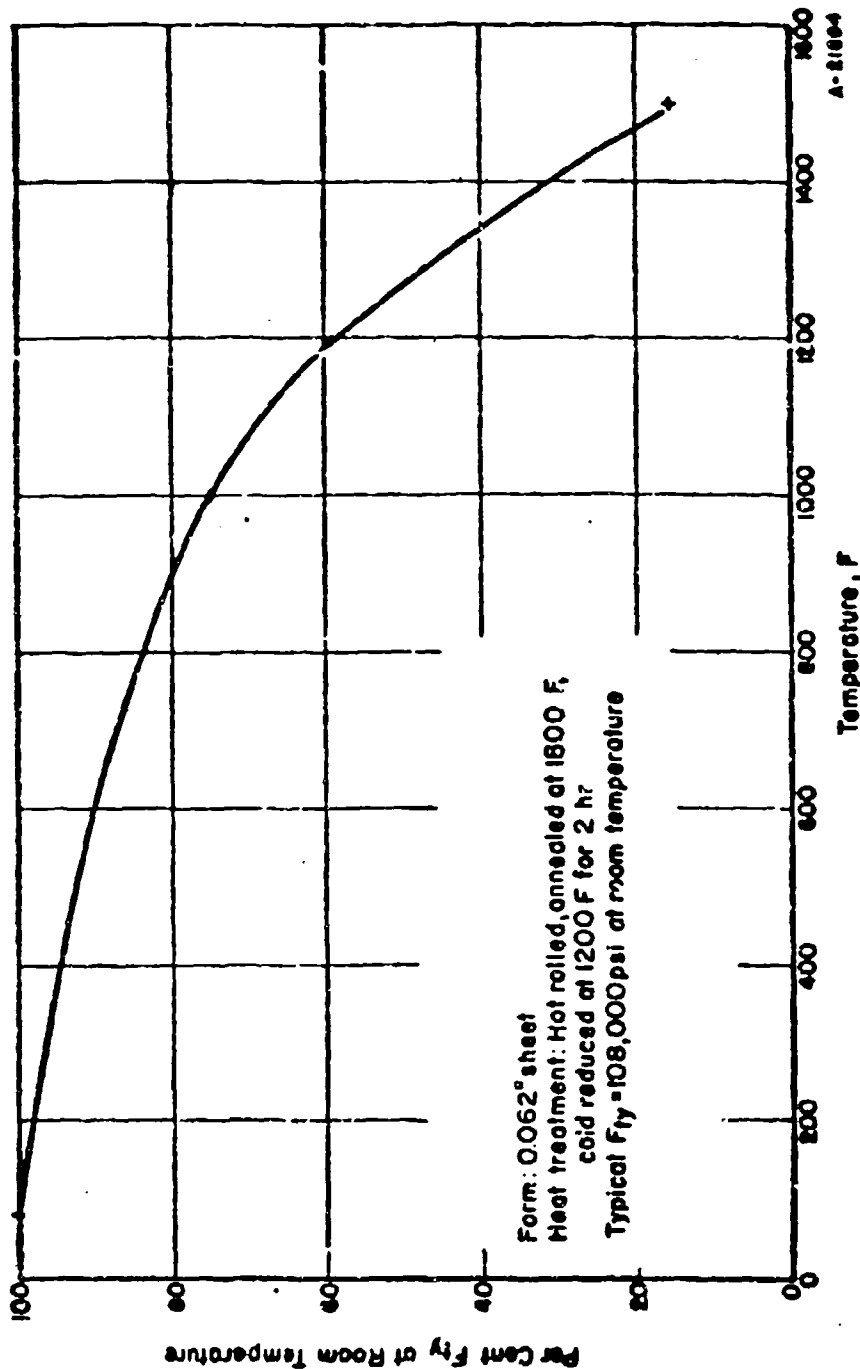


FIGURE 161. DESIGN CURVE FOR TENSILE YIELD STRENGTH (F_y) OF 19-9DL STAINLESS STEEL (HOT ROLLED) AT ELEVATED TEMPERATURE

Ref. 29, Data Sheet 22.

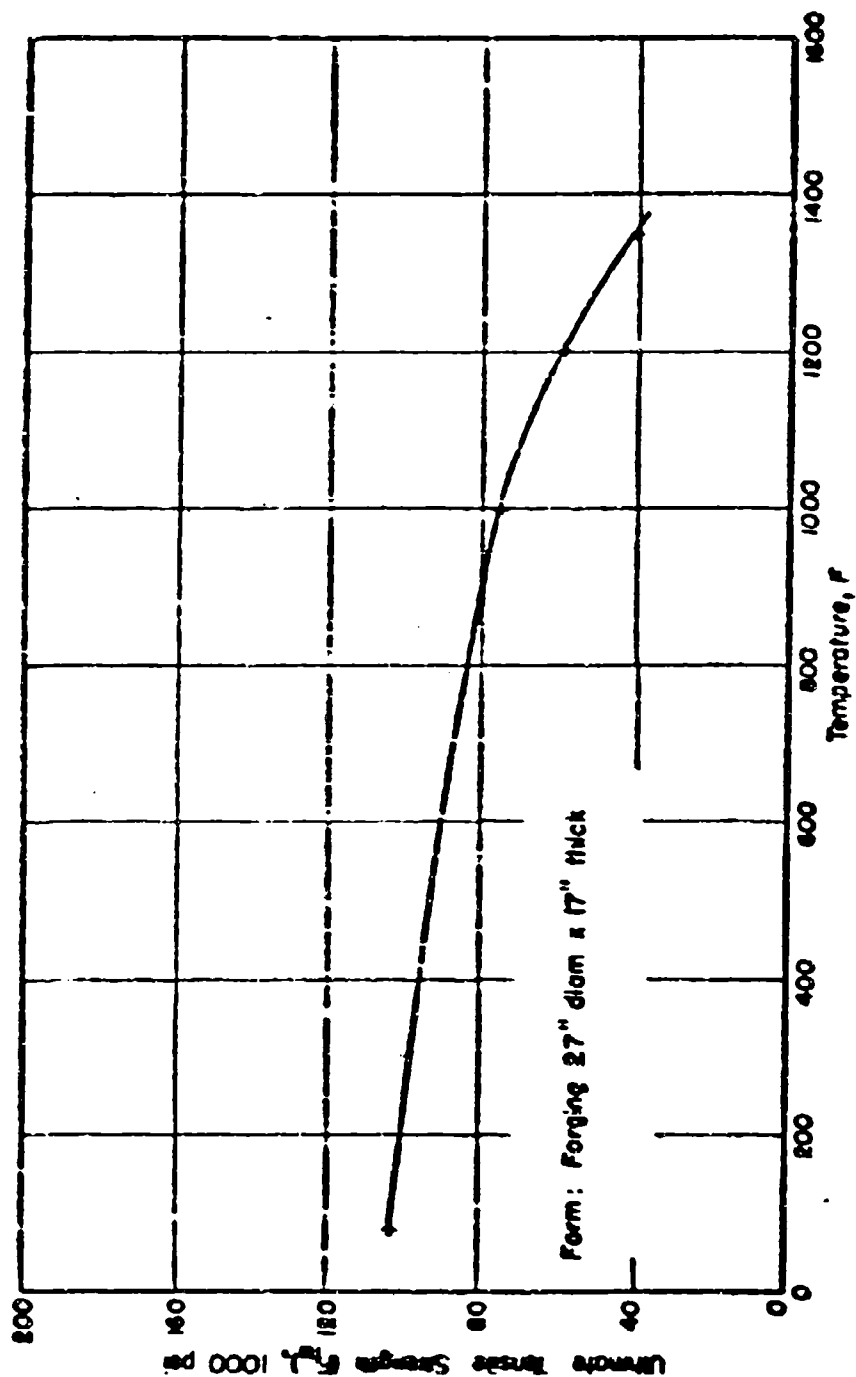


FIGURE 163. TENSILE STRENGTH (F_u) OF 19-9DL STAINLESS STEEL (FORGING) AT ELEVATED TEMPERATURE

Ref. 29, Data Sheet 19.

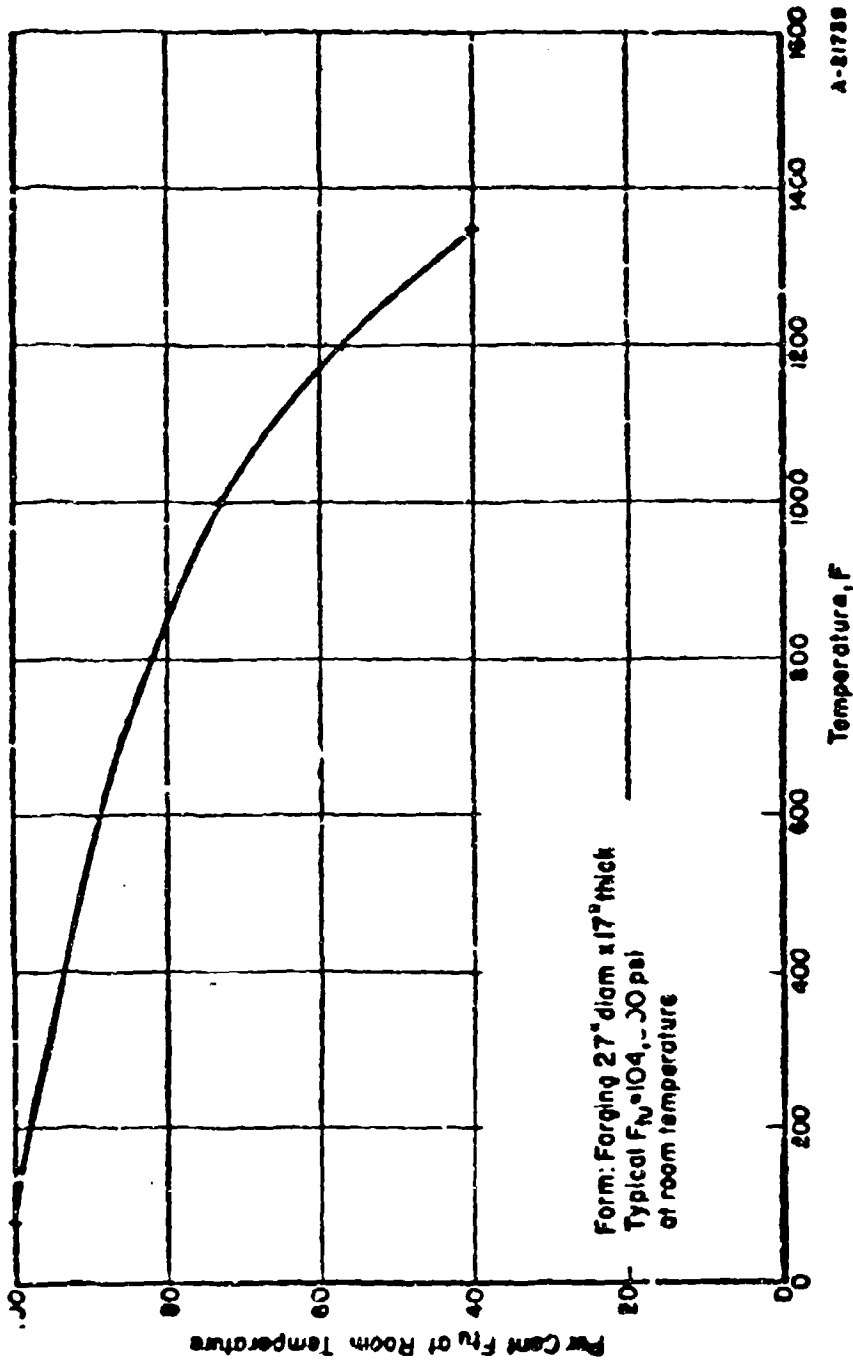


FIGURE 164. DESIGN CURVE FOR TENSILE STRENGTH (F_u) OF 19-97L STAINLESS STEEL (FORGING) AT ELEVATED TEMPERATURE

Ref. 29, Data Sheet 19.

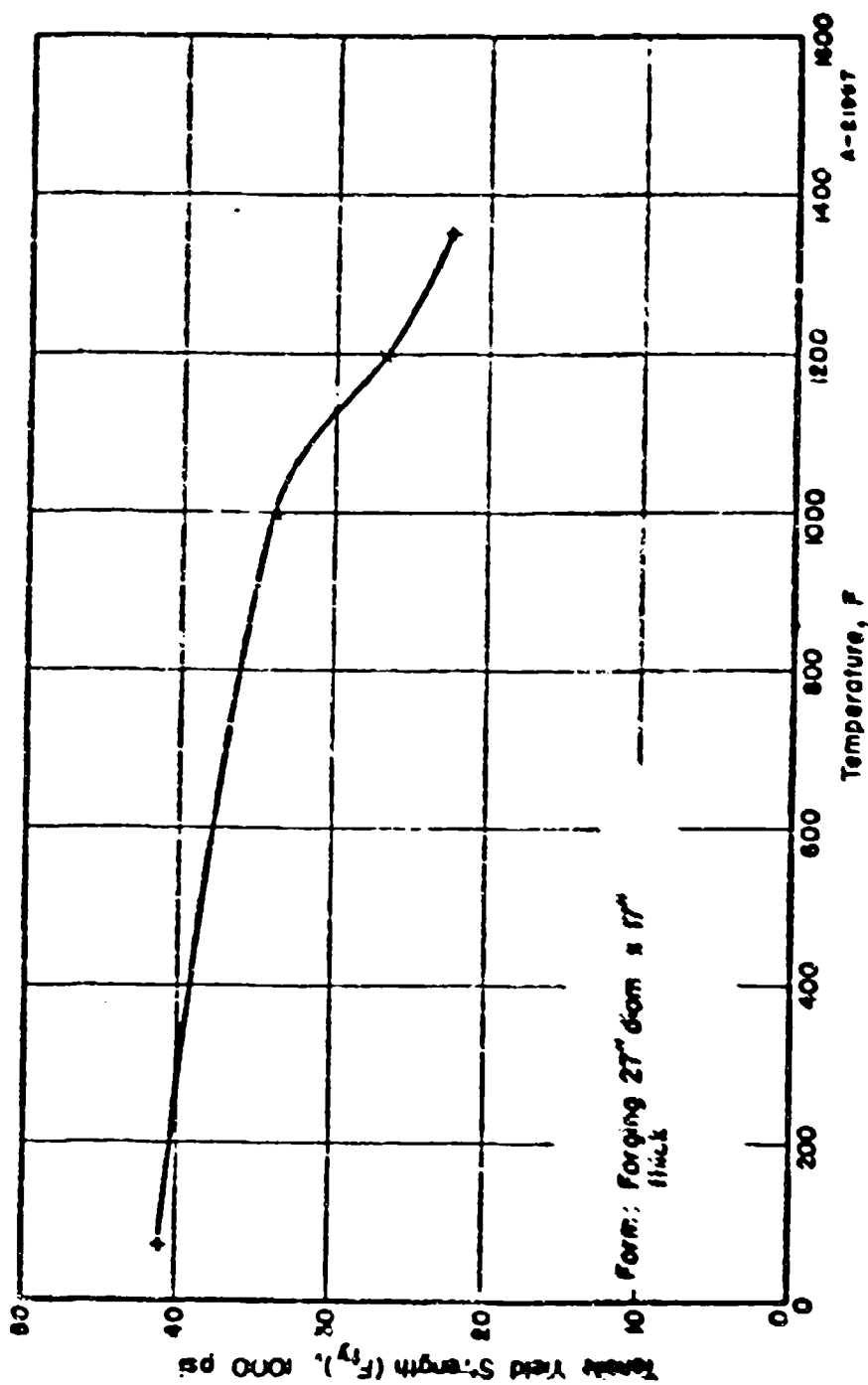


FIGURE 165. TENSILE YIELD STRENGTH (F_y) OF 19-3DL STAINLESS STEEL (FORGING) AT ELEVATED TEMPERATURE

Ref. 29, Data Sheet 19.

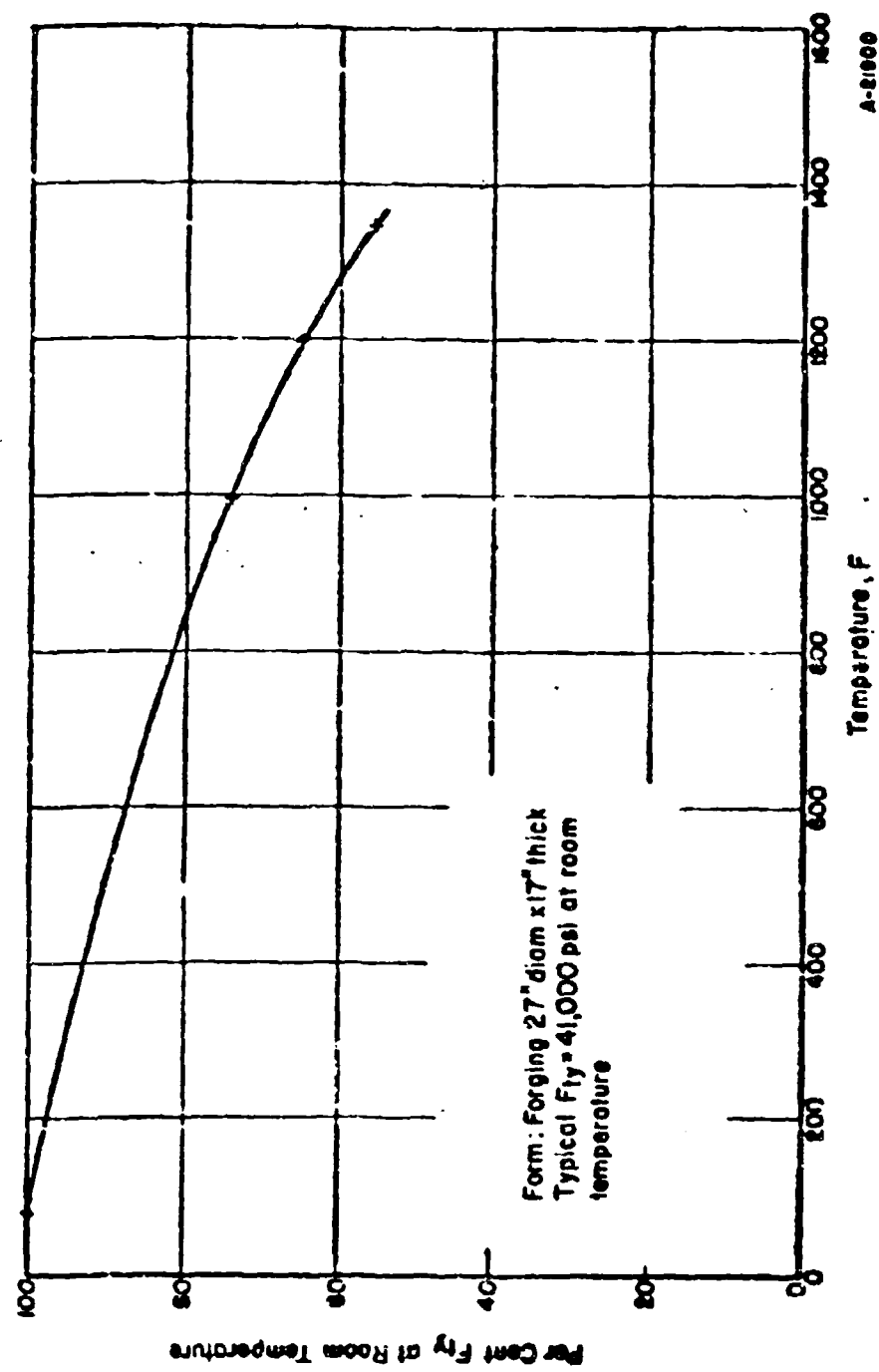


FIGURE 166. DESIGN CURVE FOR TENSILE YIELD STRENGTH (F_y) OF 19-9DL STAINLESS STEEL (FORGING) AT ELEVATED TEMPERATURE

Ref. 29, Data Sheet 19.

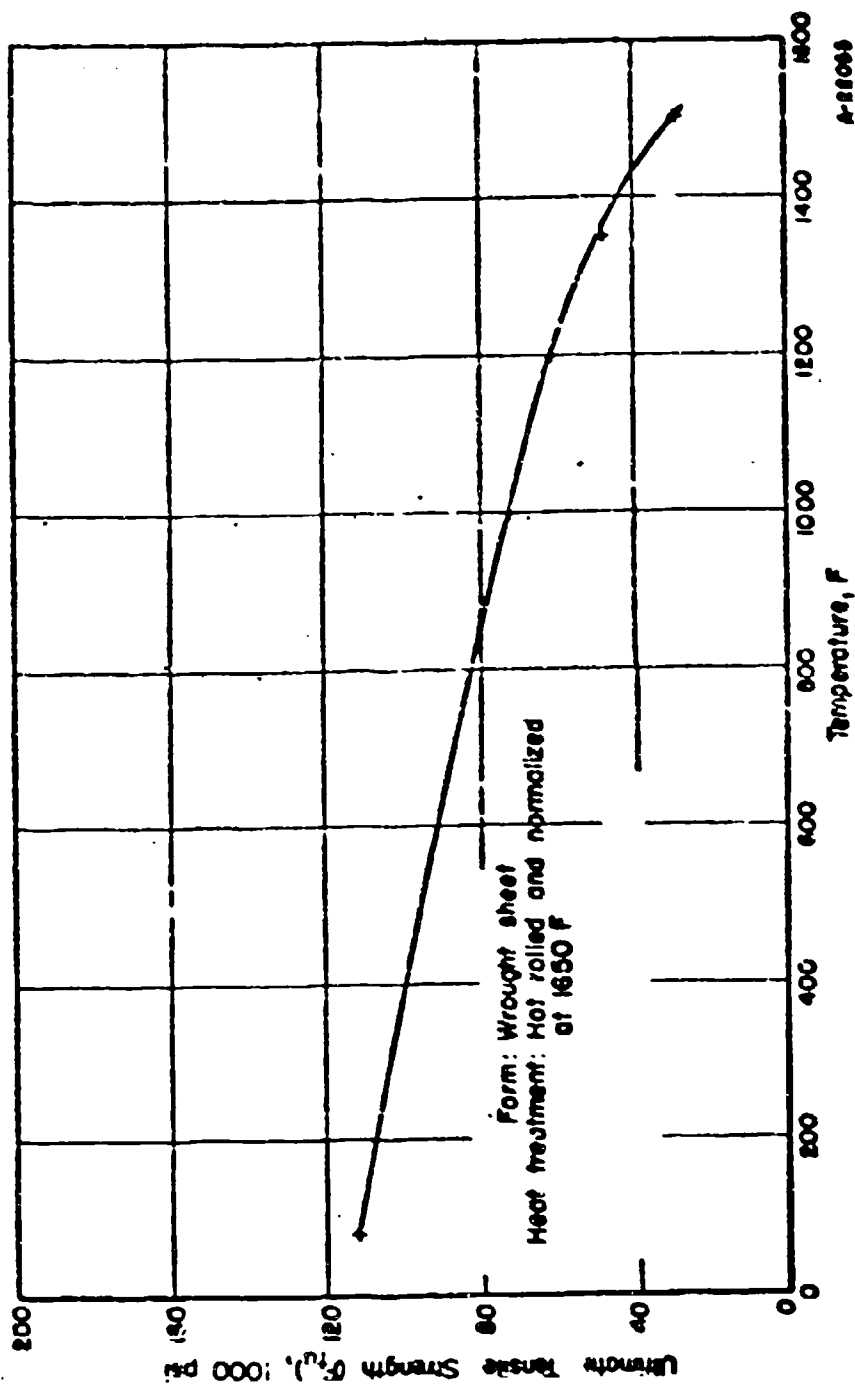


FIGURE 167. TENSILE STRENGTH (F_u) OF 19-9DL STAINLESS STEEL (HOT ROLLED) AT ELEVATED TEMPERATURE

Ref. 29, Data Sheet 25.

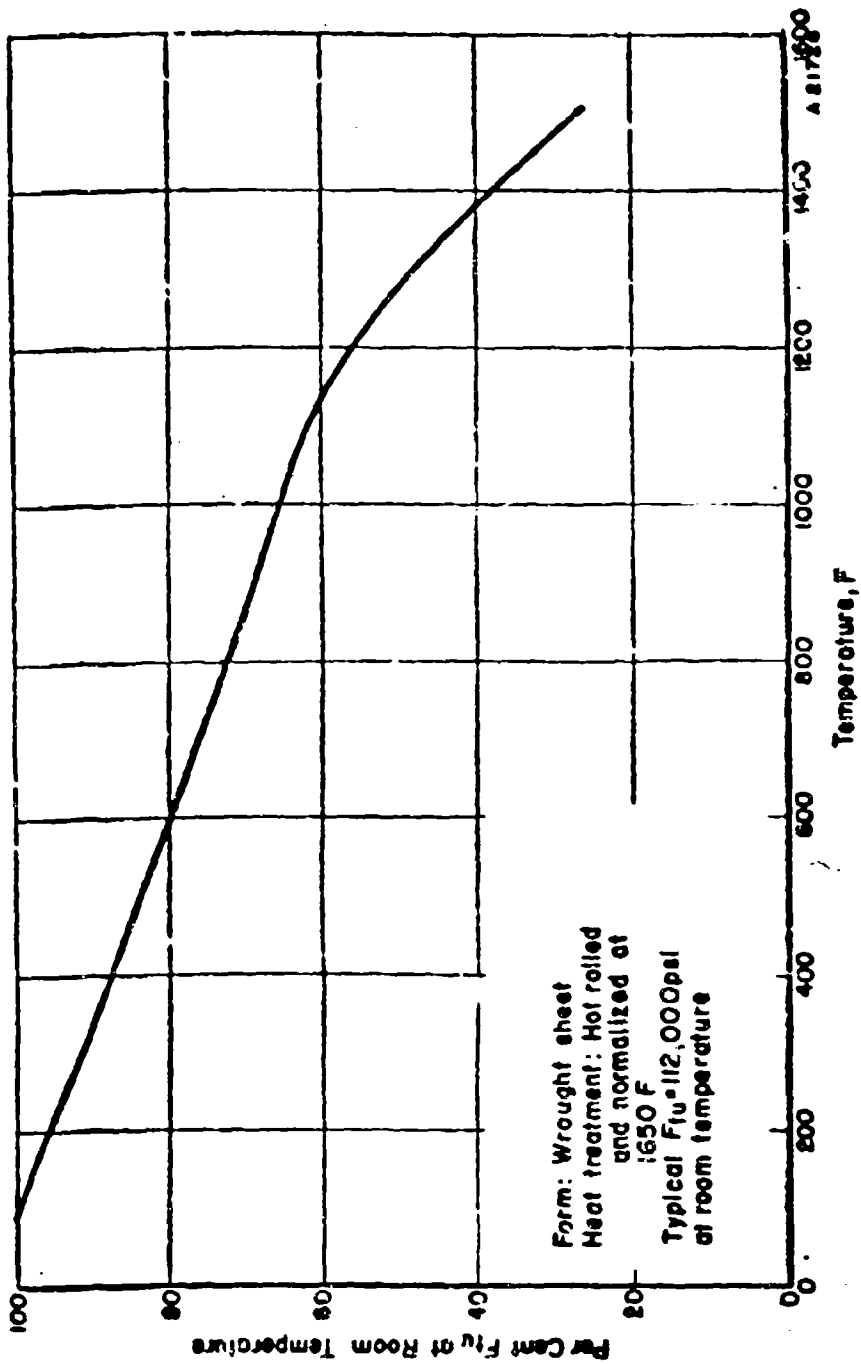


FIGURE 168. DESIGN CURVE FOR TENSILE STRENGTH (F_u) OF 19-9DL STAINLESS STEEL
(HOT ROLLED) AT ELEVATED TEMPERATURE

Ref. 29, Data Sheet 25.

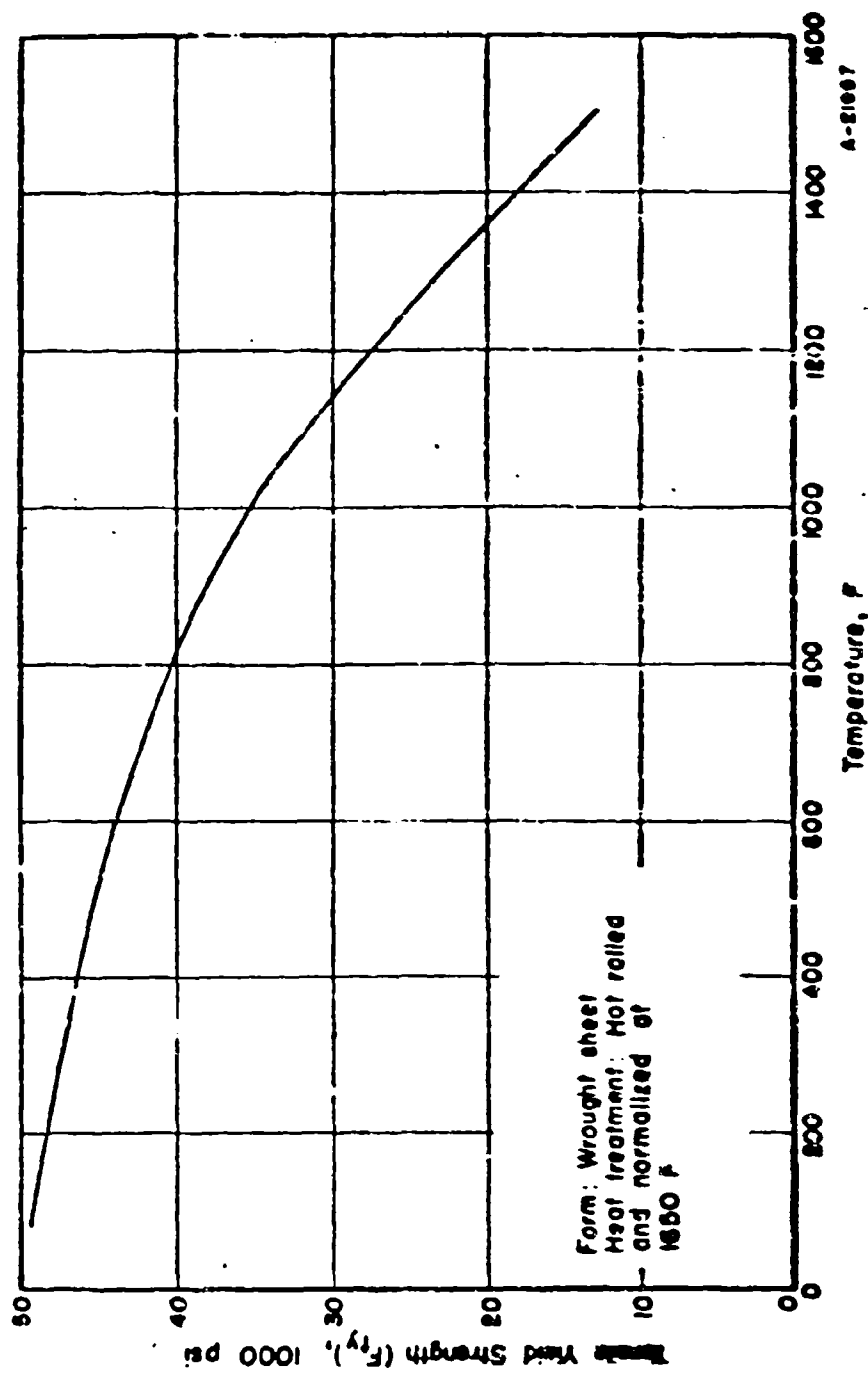


FIGURE 169. TENSILE YIELD STRENGTH (F_y) OF 19-9DL STAINLESS STEEL (HOT ROLLED) AT ELEVATED TEMPERATURE

Ref. 29, Data Sheet 25.

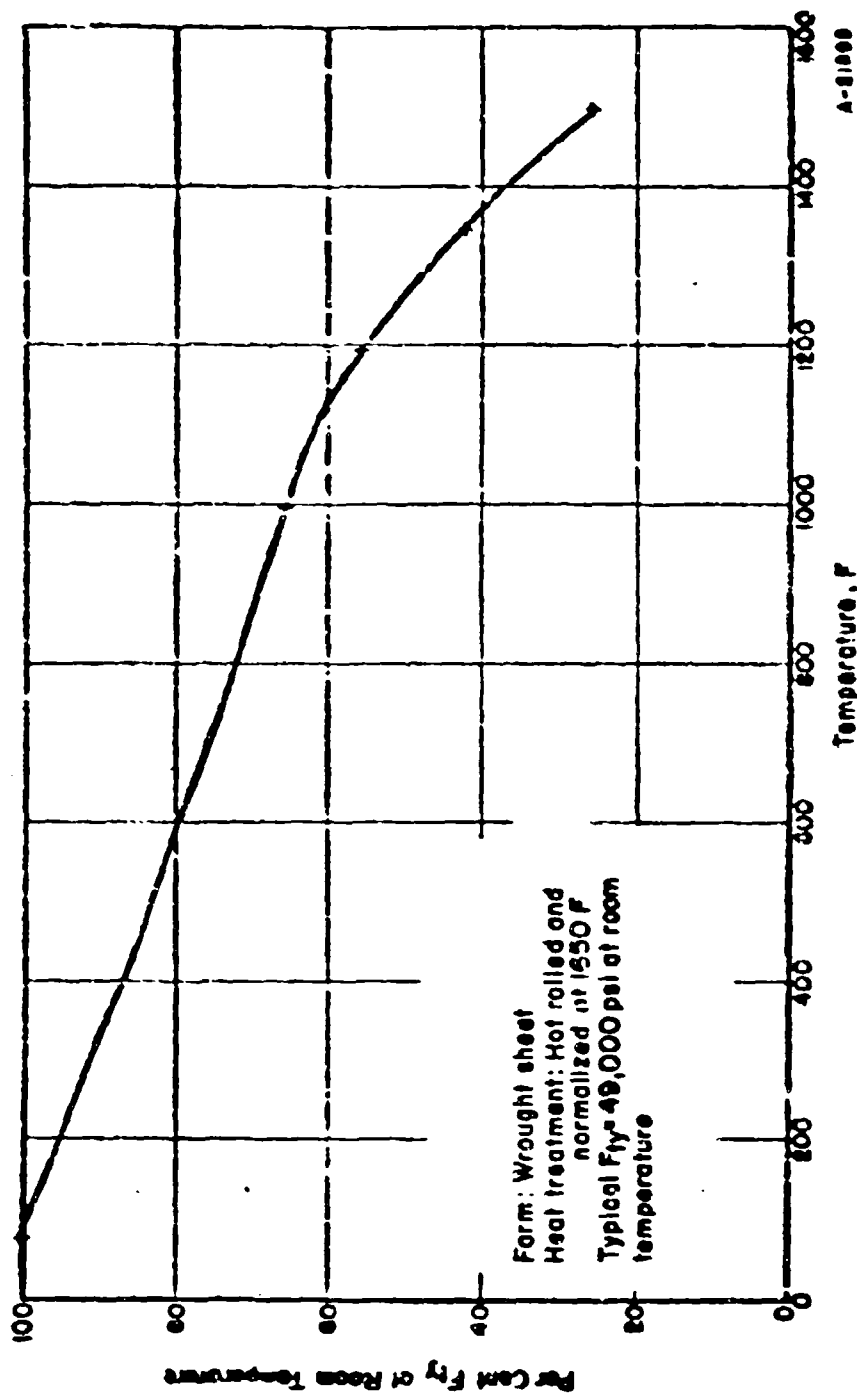


FIGURE 170. DESIGN CURVE FOR TENSILE STRENGTH (F_t) OF 19-9DL STAINLESS STEEL (HOT ROLLED) AT ELEVATED TEMPERATURE
Ref. 29, Data Sheet 25.

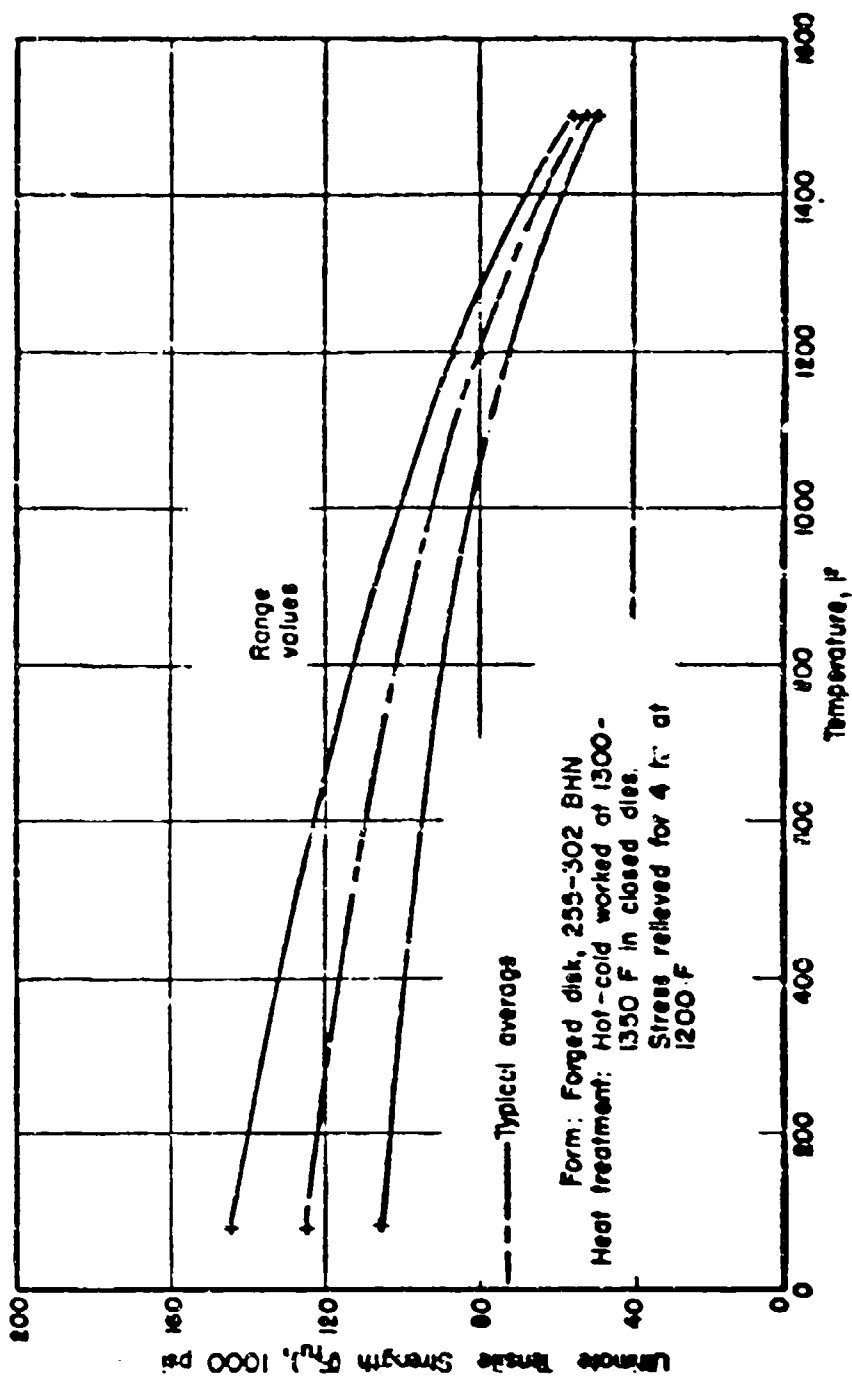


FIGURE 171. TENSILE STRENGTH (F_u) OF 19-9DL STAINLESS STEEL (HOT-COLD WORKED) AT ELEVATED TEMPERATURE

Ref. 29, Data Sheet 17.

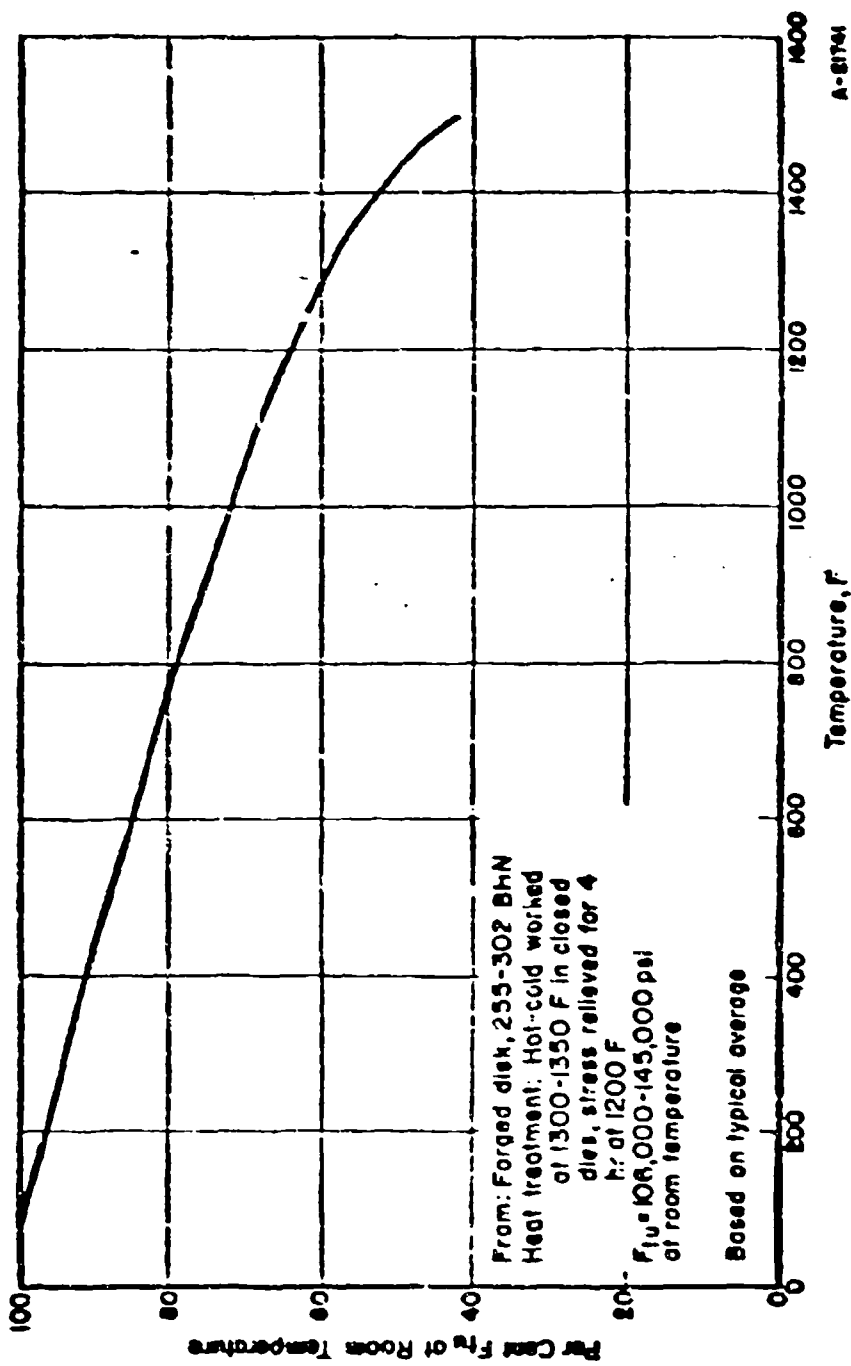


FIGURE 172. DESIGN CURVE FOR TENSILE STRENGTH (F_{tu}) OF 19-9DL STAINLESS STEEL (HOT-COLD WORKED) AT ELEVATED TEMPERATURE

Ref. 29, Data Sheet 17.

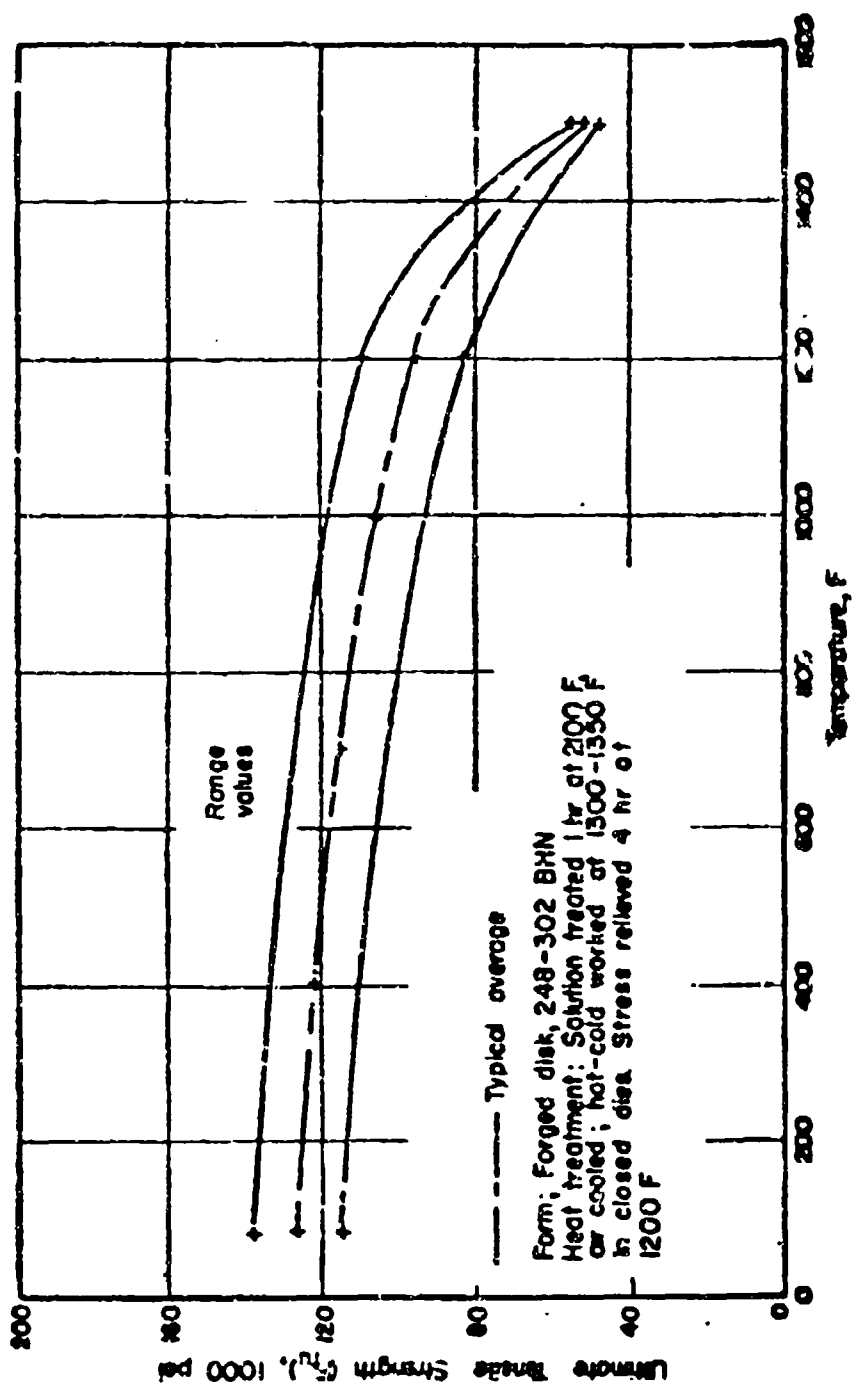


FIGURE 173. TENSILE STRENGTH (F_u) OF 19-9DL STAINLESS STEEL (HOT-COLD WORKED) AT ELEVATED TEMPERATURE

Ref. 29, Data Sheet 16.

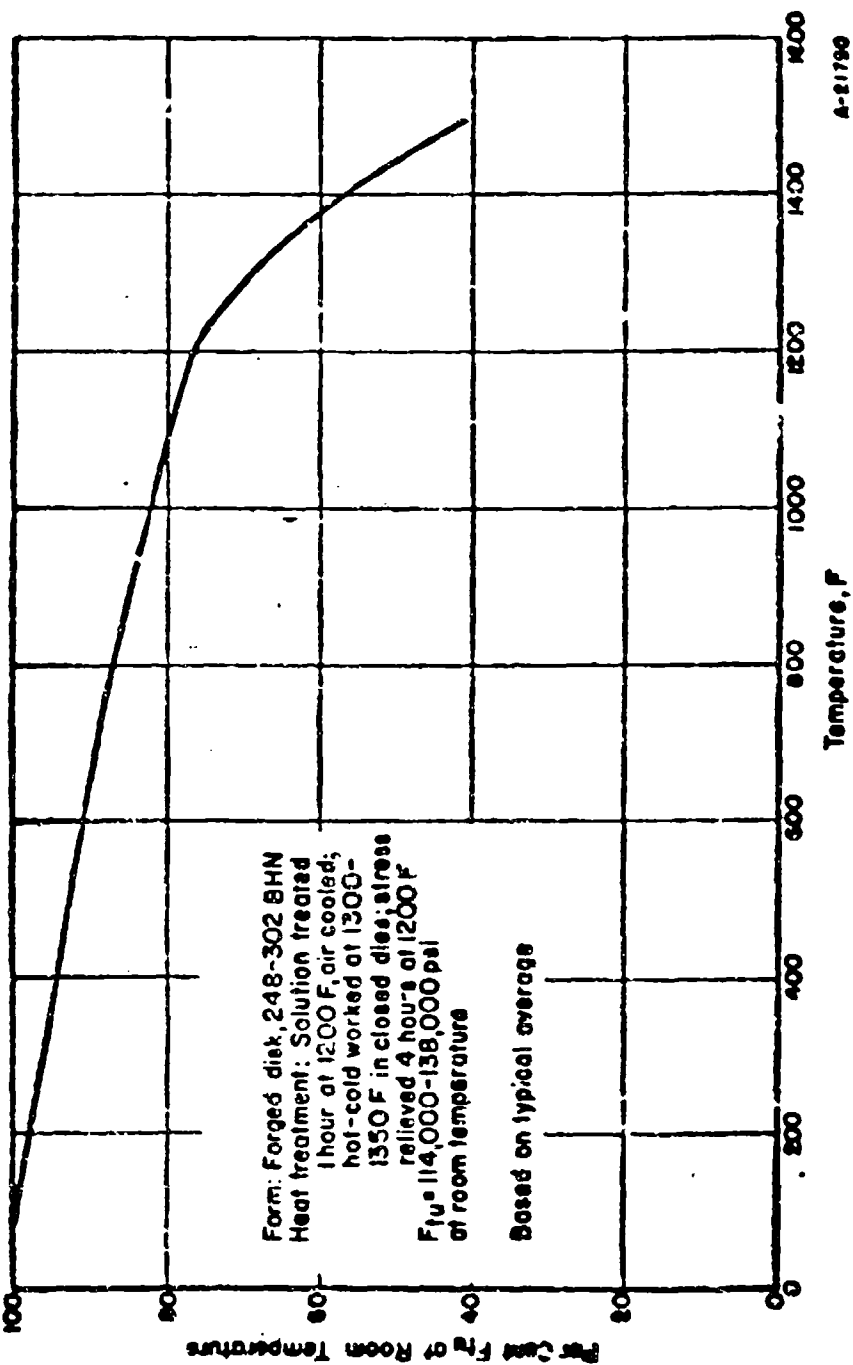


FIGURE 114. DESIGN CURVE FOR TENSILE STRENGTH (F_{TU}) OF 19-9DL STAINLESS STEEL
 (HOT-COLD WORKED) AT ELEVATED TEMPERATURE

Ref. 29, Data Sheet 16.

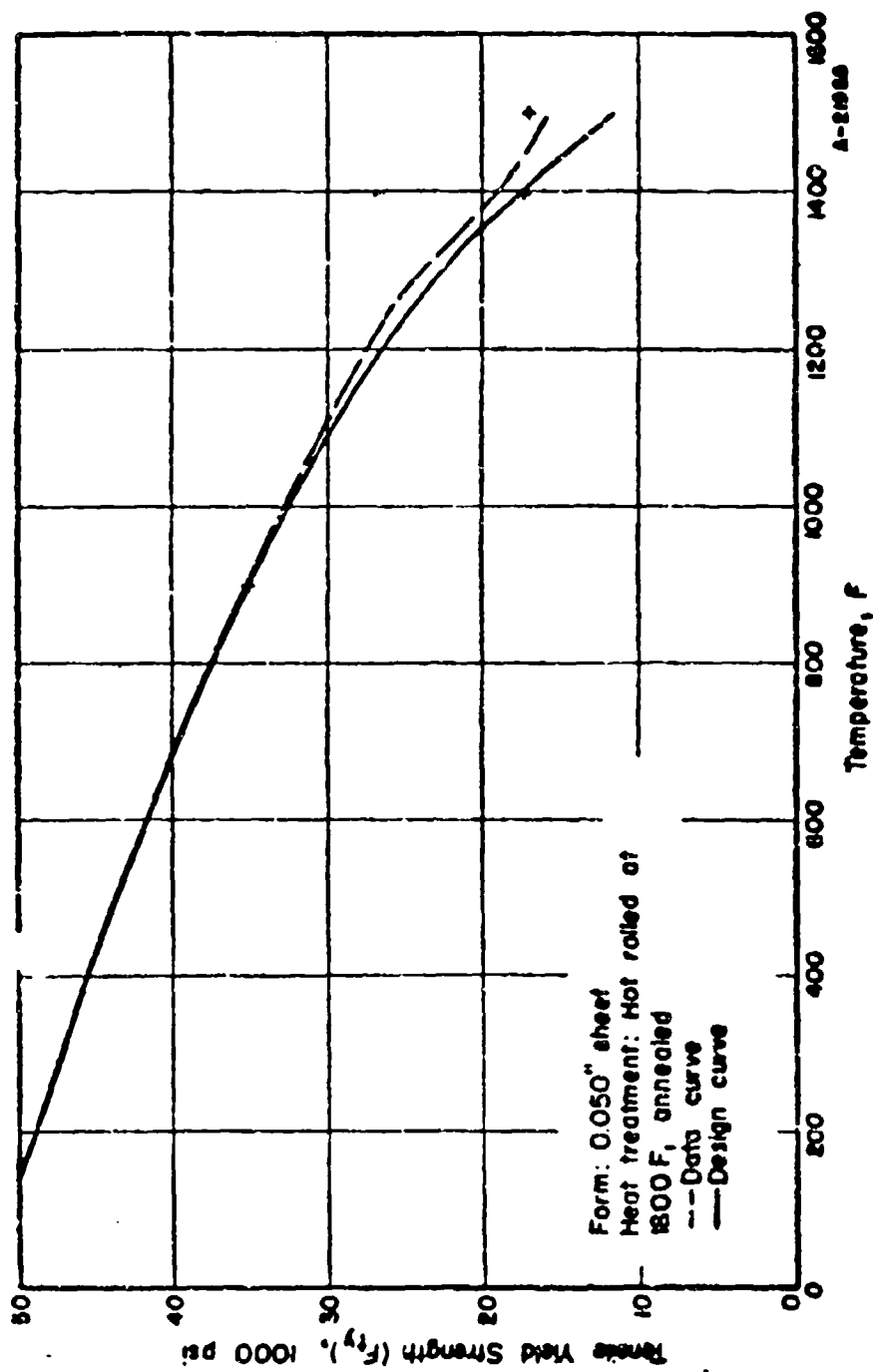


FIGURE 175. TENSILE YIELD STRENGTH (F_y) OF 19-9DL STAINLESS STEEL (HOT ROLLED) AT ELEVATED TEMPERATURE

Ref. 29, Data Sheet 23.

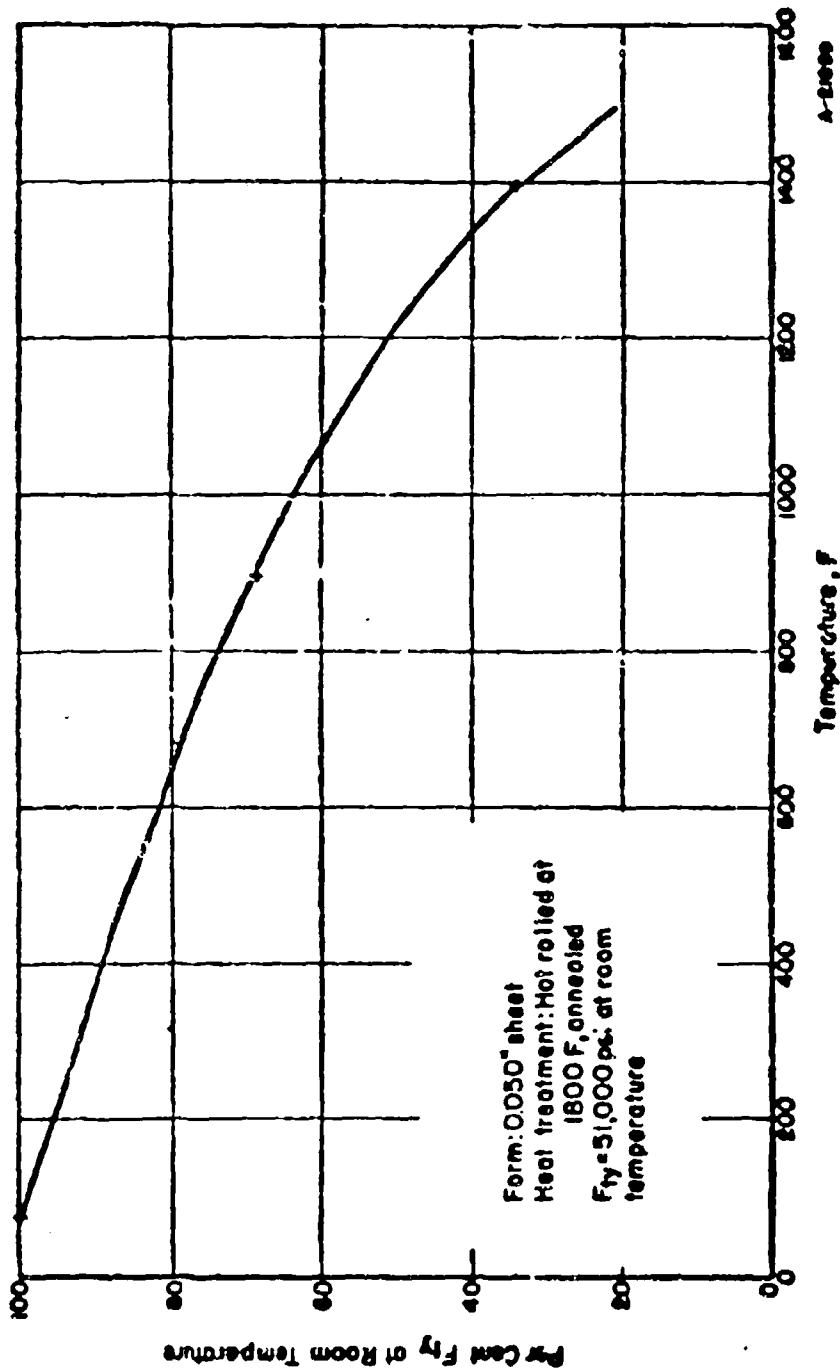


FIGURE 176. DESIGN CURVE FOR TENSILE YIELD STRENGTH (F_y) OF 19-9DL STAINLESS STEEL (HOT ROLLED) AT ELEVATED TEMPERATURE

Ref. 29, Data Sheet 23.

19-9DX ALLOY
(AMS-5538) (AMS-5539)

The 19-9DX alloy was developed in 1950 as a columbium-free version of 19-9DL because of the scarcity of columbium at that time. It was found that if the columbium were eliminated in favor of somewhat higher titanium and molybdenum content, an alloy resulted which had equivalent properties at a lower strategic index. The typical chemical composition of 19-9DX is given in Table 11.

**TABLE 11. TYPICAL CHEMICAL
COMPOSITION OF
19-9DX HEAT-
RESISTANT ALLOY
(AMS-5538) (AMS-5539)**

Element	Weight Per Cent
Carbon	0.30
Manganese	1.25
Silicon	0.55
Nickel	9.00
Chromium	19.00
Molybdenum	1.50
Tungsten	1.25
Titanium	0.60
Iron	Balance

The metallurgy of 19-9DX is similar to that of 19-9DL; 19-9DX is essentially austenitic. Alloy 19-9DX is usually used in the annealed or stress-relieved condition for temperatures below approximately 1300 F and in the solution-treated and aged condition above approximately 1300 F. Other conditions have found use in various applications. The minimum mechanical properties of 19-9DX in the annealed condition are given in Table 12; properties of 19-9DX in the stress-relieved condition are given in Table 13.

**TABLE 12. MINIMUM MECHANICAL PROPERTIES OF
19-9DX ALLOY (AMS-5538)**

Property	
Ultimate tensile (F_{tu})	95,000-120,000 psi
Tensile yield (F_{ty})	45,000 psi (minimum)
Elongation: (e) in 2 inches	10 per cent (minimum)

TABLE 13. MINIMUM MECHANICAL PROPERTIES OF
19-9DX ALLOY (AMS-5539)

Property	
Ultimate tensile (F_{tu})	125,000 psi (minimum)
Tensile yield (F_{ty})	90,000 psi (minimum)
Elongation (e) in 2 inches	12 per cent (minimum)

The short-time, elevated-temperature properties of 19-9DX are shown in the following curves:

- (1) Tensile properties, Figures 177 through 182 and 189 through 194
- (2) Compressive properties, Figures 183, 184, 195, and 193
- (3) Bearing properties, Figures 185 through 188 and 197 through 197.

Stress-strain curves and data on shear strength and modulus are lacking for 19-9DX.

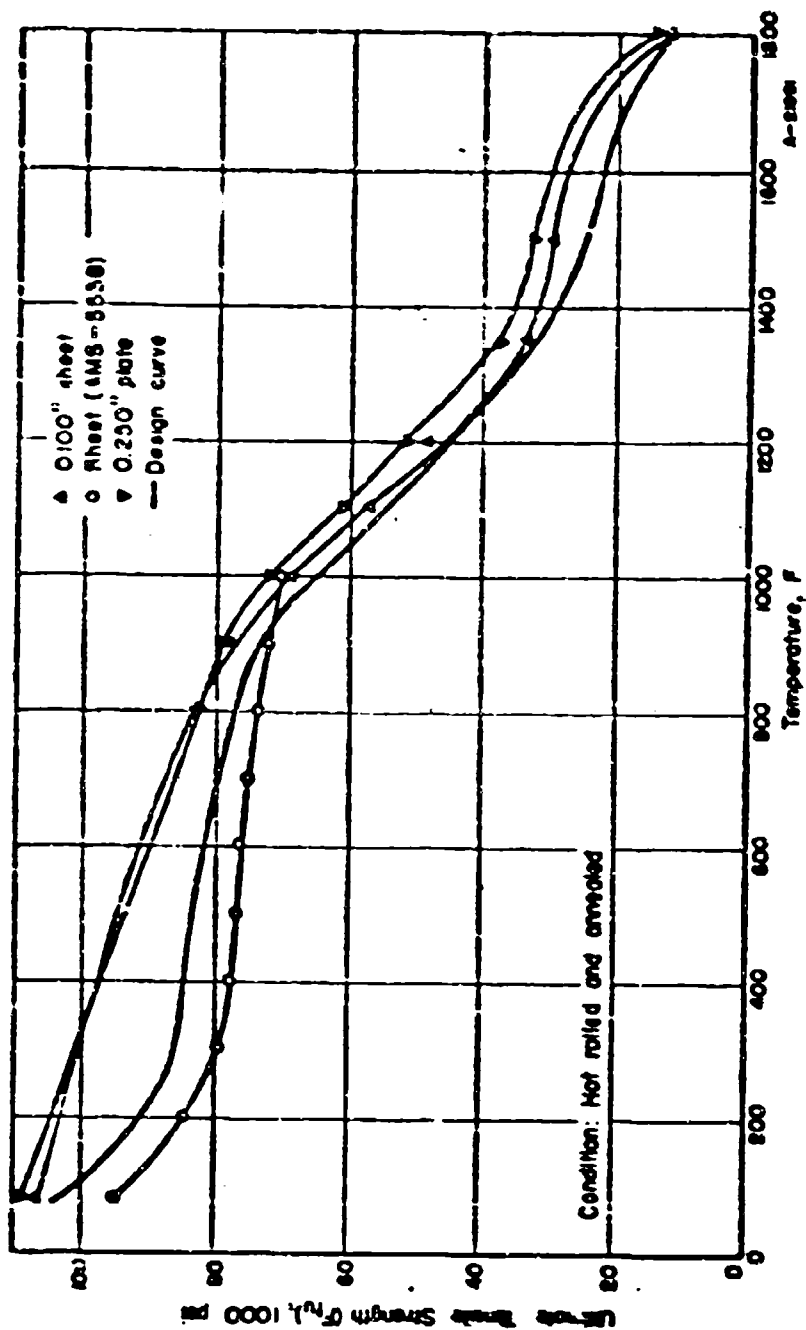


FIGURE 177. TENSILE STRENGTH (F_u) OF 19-9DX (AMS-5538) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 207.241.

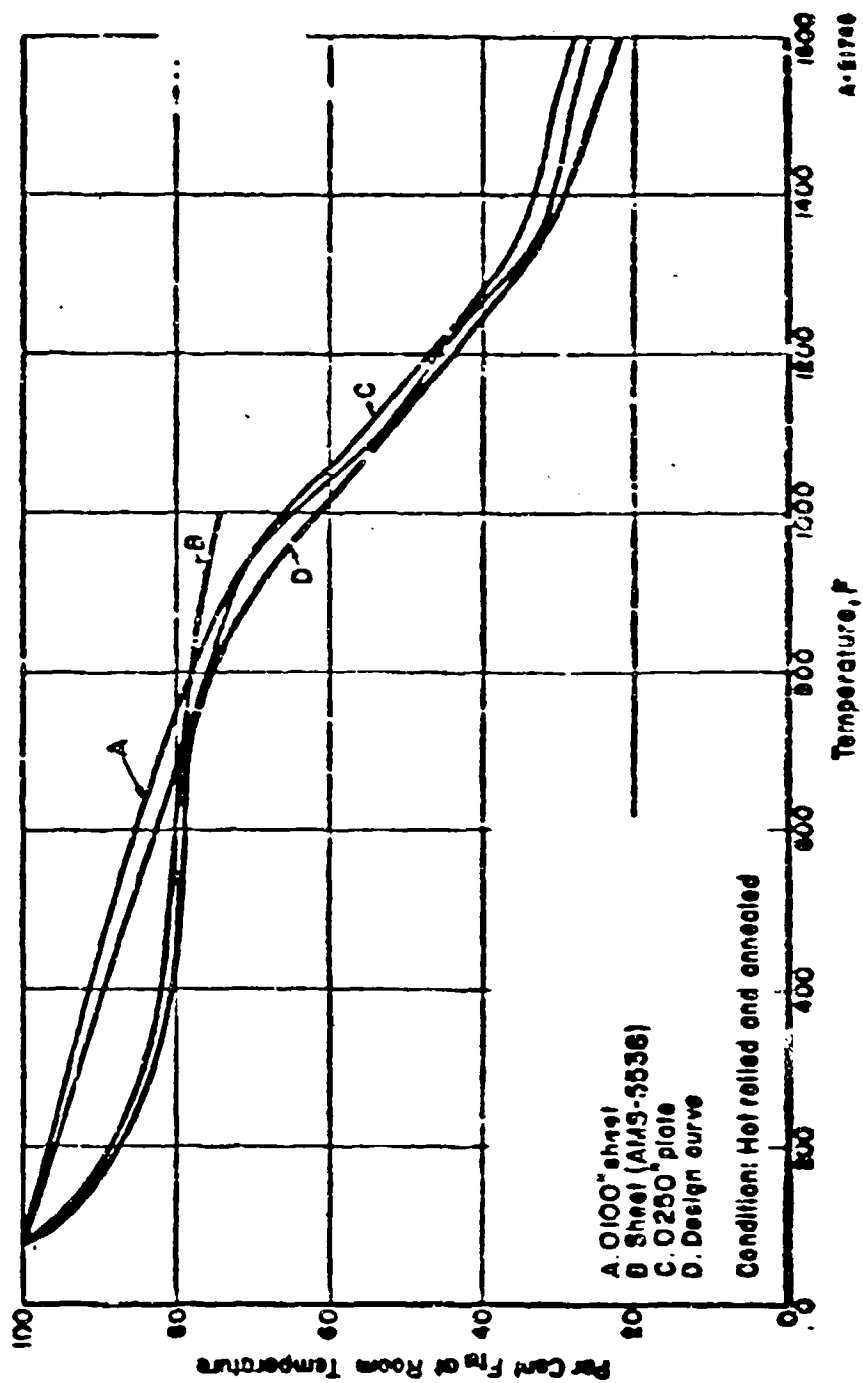


FIGURE 178. TENSILE STRENGTH (F_u) OF 19-9DX (AMS-5538) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 207, 241.

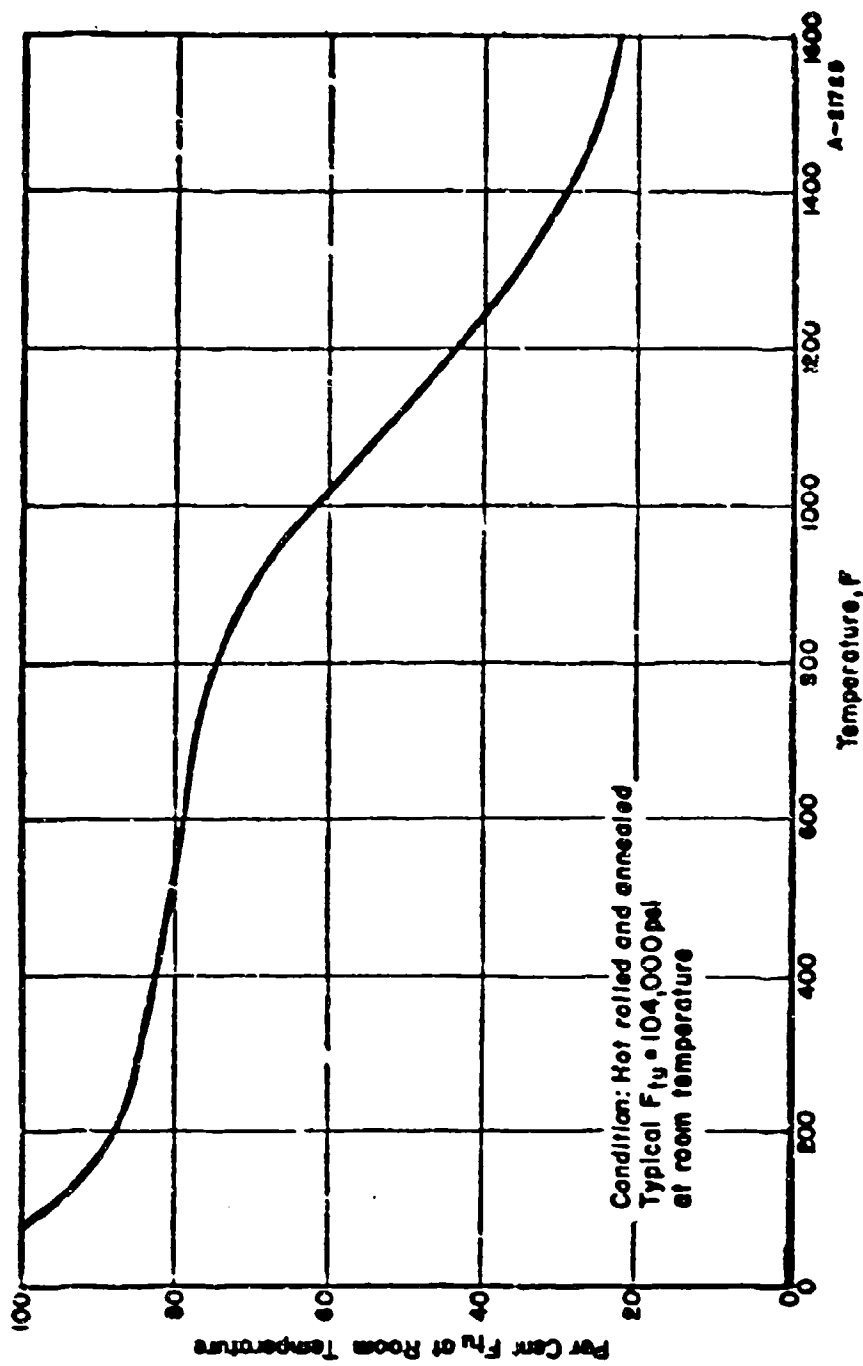


FIGURE 179. DESIGN CURVE FOR TENSILE STRENGTH (F_u) OF 19-9DX (AMS-5519) STAINLESS STEEL AT ELEVATED TEMPERATURE

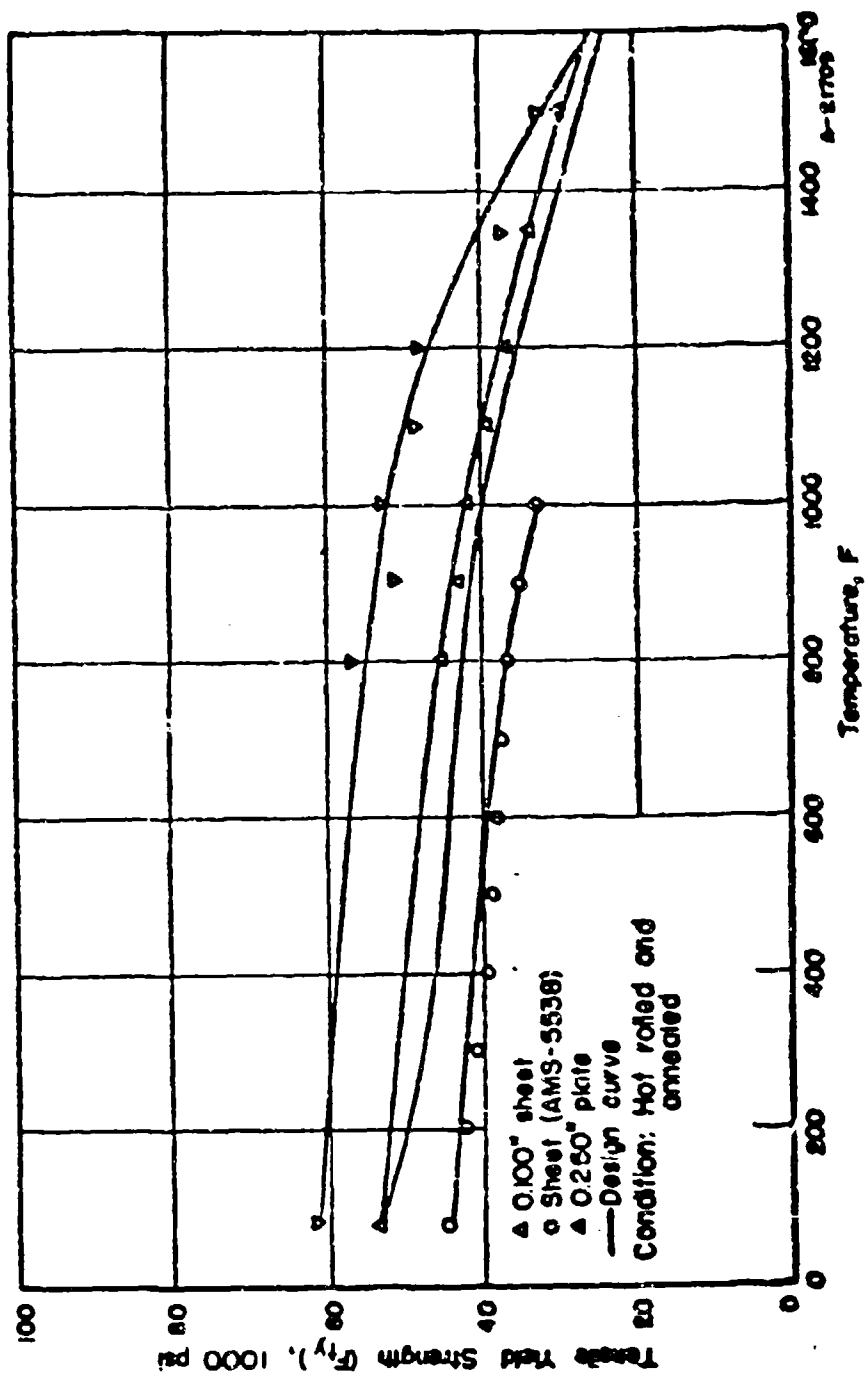


FIGURE 180. TENSILE YIELD STRENGTH (F_y) OF 19-9DX (AMS-5538) STAINLESS STEEL AT ELEVATED TEMPERATURE

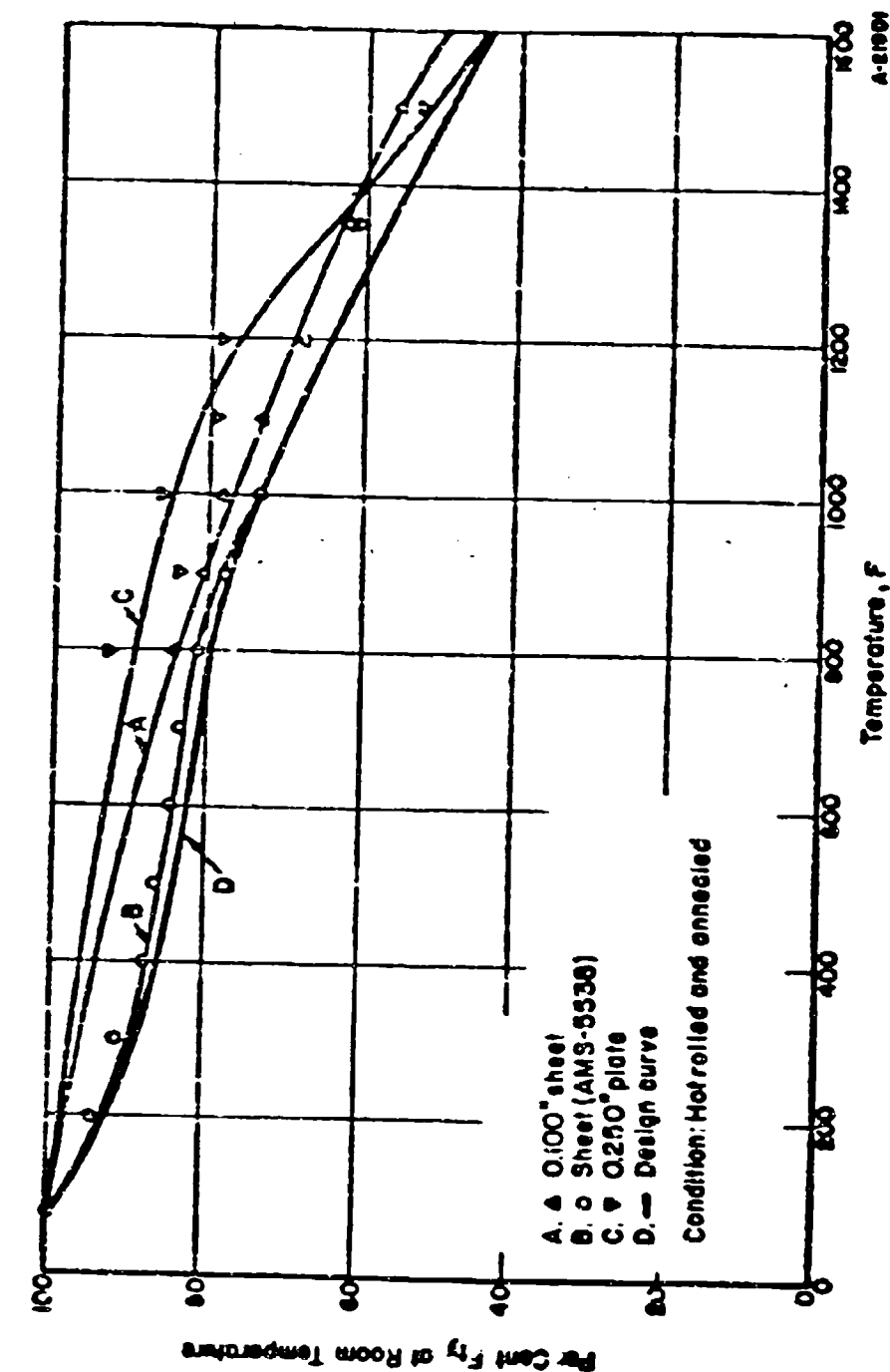


FIGURE 181. TENSILE YIELD STRENGTH (F_y) EXPRESSED AS A PERCENTAGE OF ROOM-TEMPERATURE TENSILE YIELD STRENGTH OF 19-9DX (AMS-5536) STAINLESS STEEL AT ELEVATED TEMPERATURE

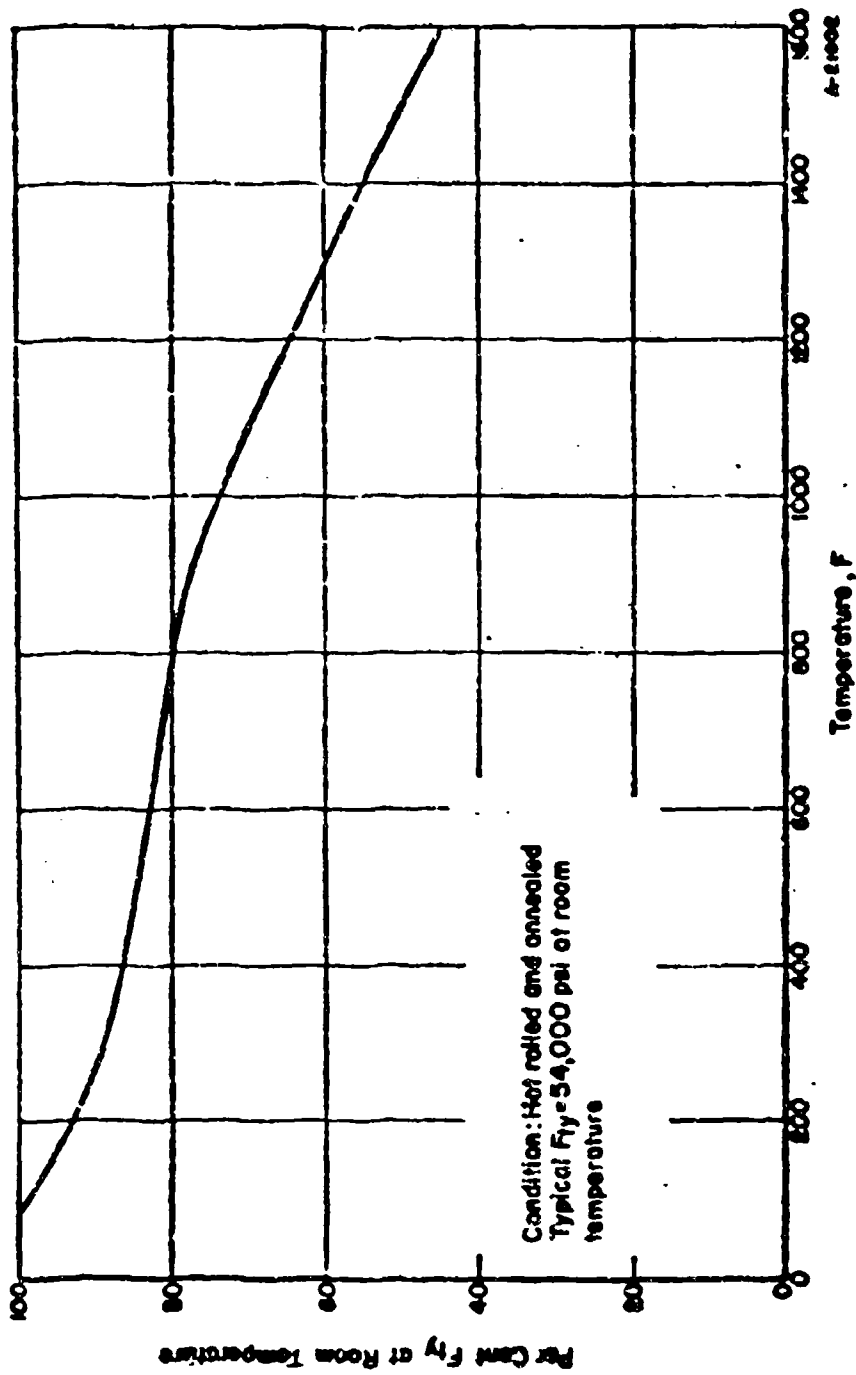


FIGURE 182. DESIGN CURVE FOR TENSILE YIELD STRENGTH (F_y) OF 19-9DX (AMS-5538) STAINLESS STEEL AT ELEVATED TEMPERATURE

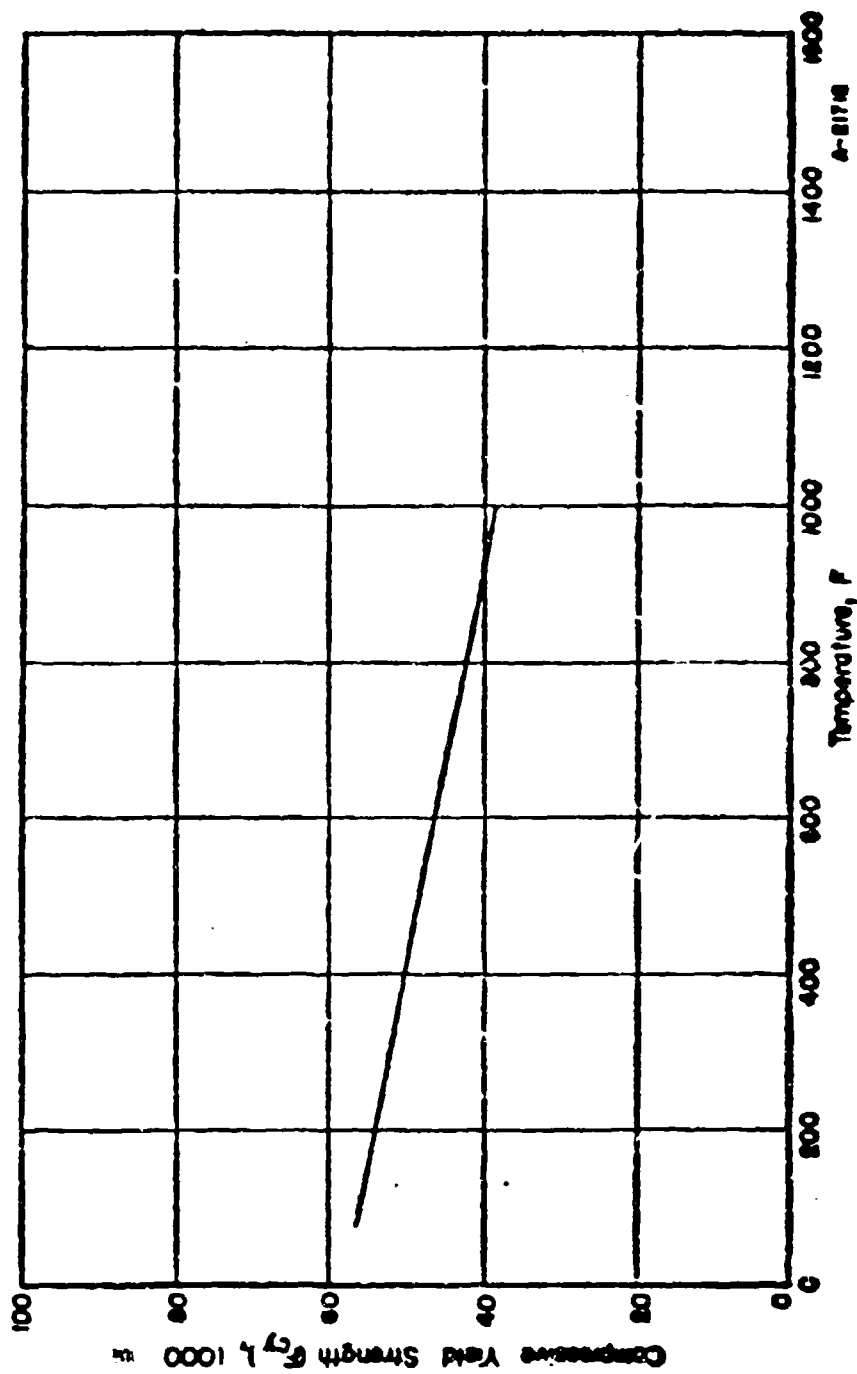


FIGURE 181. COMPRESSIVE YIELD STRENGTH (F_{cy}) OF 19-9DX (AMS-8834) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 107.

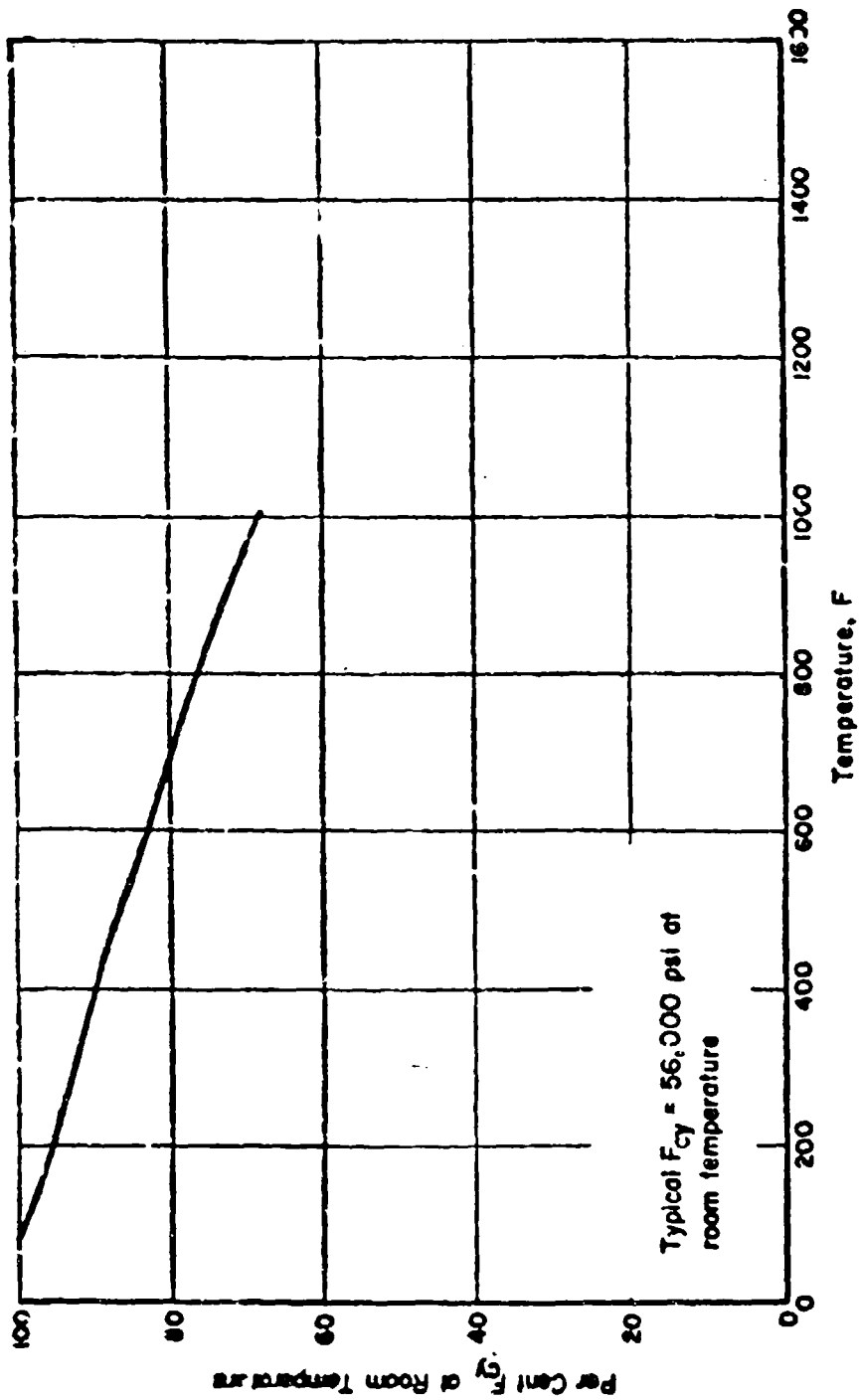


FIGURE 184. DESIGN CURVE FOR COMPRESSIVE YIELD STRENGTH (F_{cy}) OF 19-9DX (AMS-5538) STAINLESS STEEL AT ELEVATED TEMPERATURE
Ref. 207.

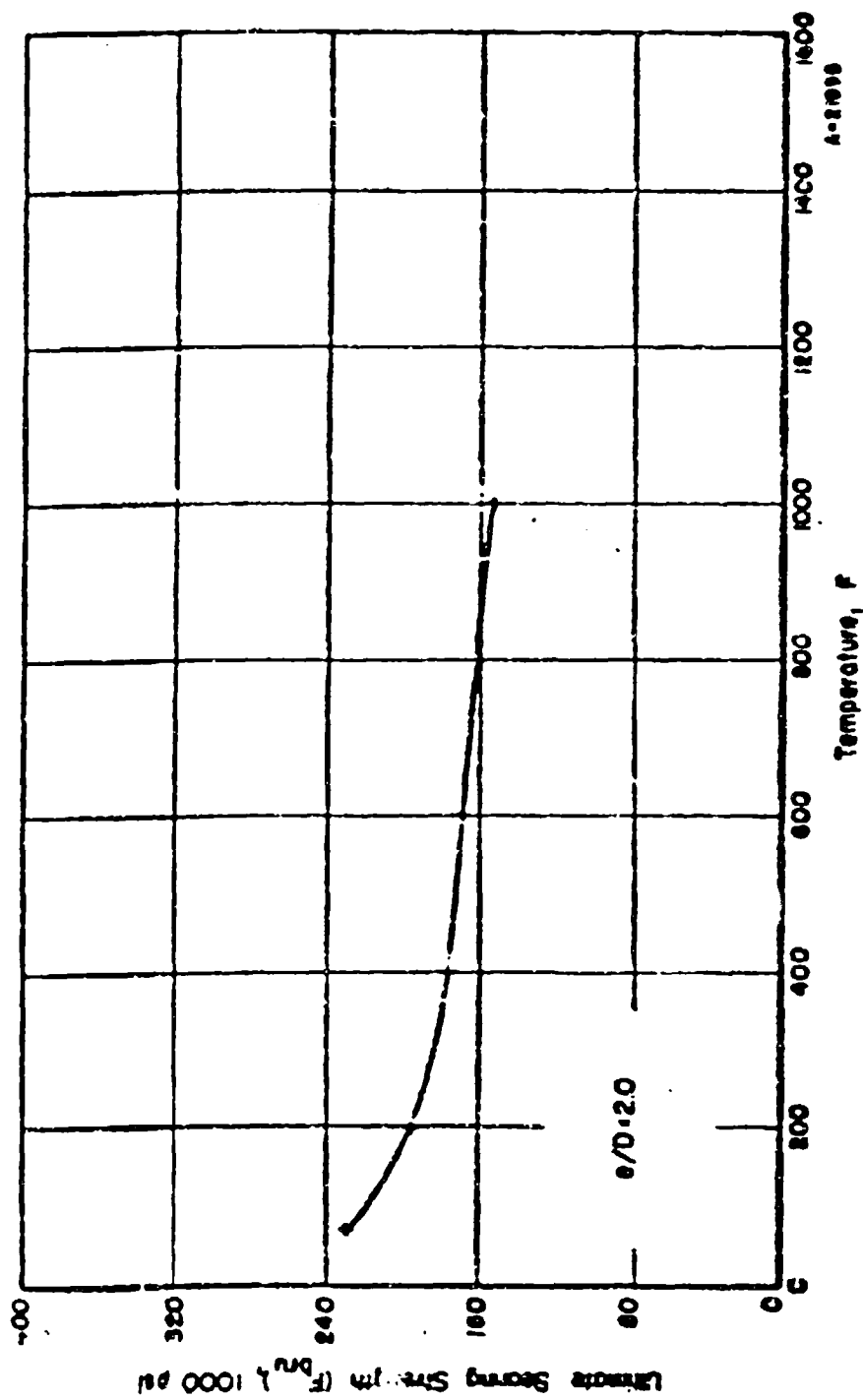


FIGURE 185. BEARING STRENGTH (F_b) OF 19-9DX (AMS-5536) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 207

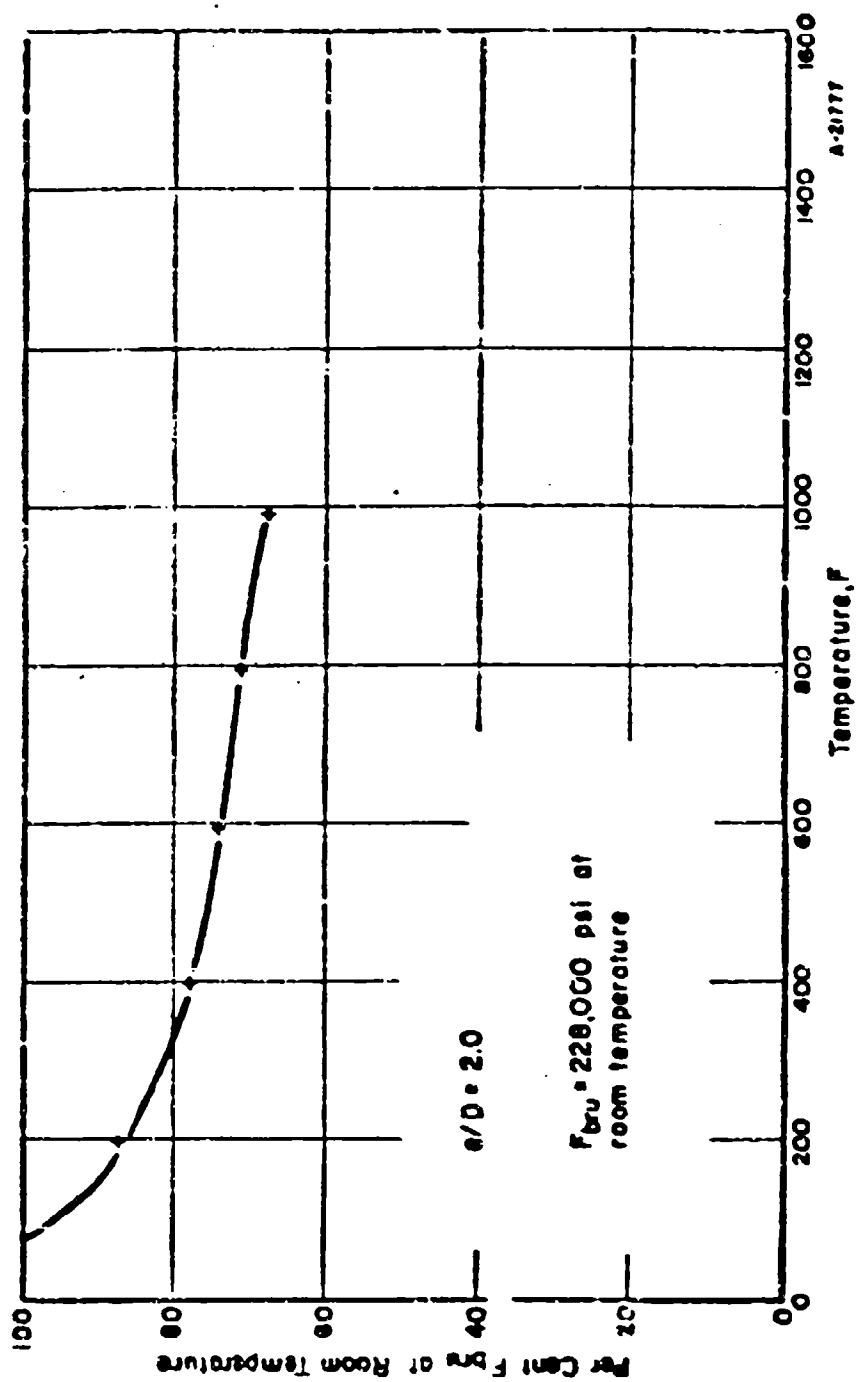


FIGURE 186. DESIGN CURVE FOR BEARING STRENGTH (F_{bru}) OF 19-9DX (AMS-5538) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 207.

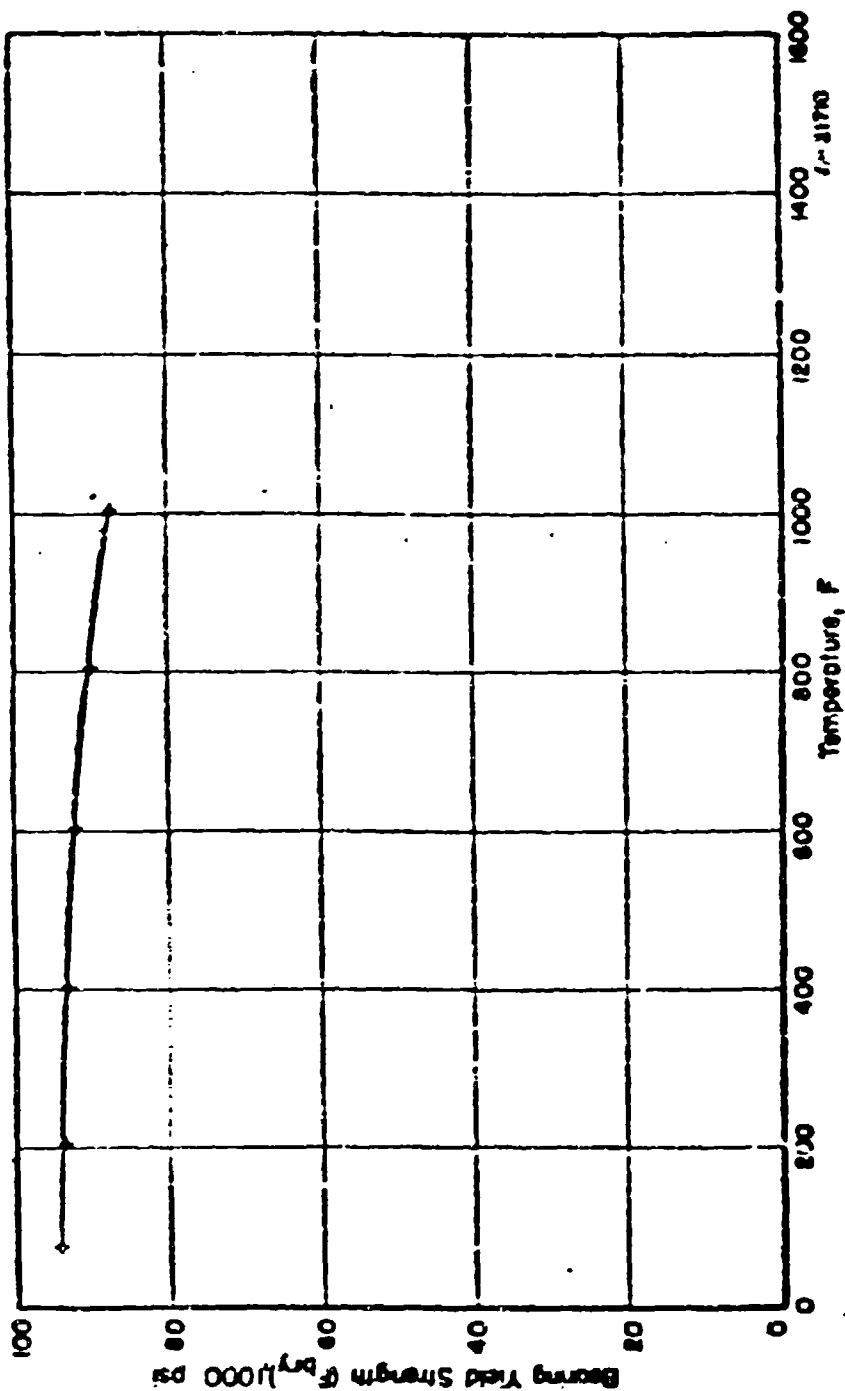


FIGURE 187. BEARING YIELD STRENGTH (F_{by}) OF 19-9DX (AMS-5538) STAINLESS STEEL AT ELEVATED TEMPERATURE
Ref. 207.

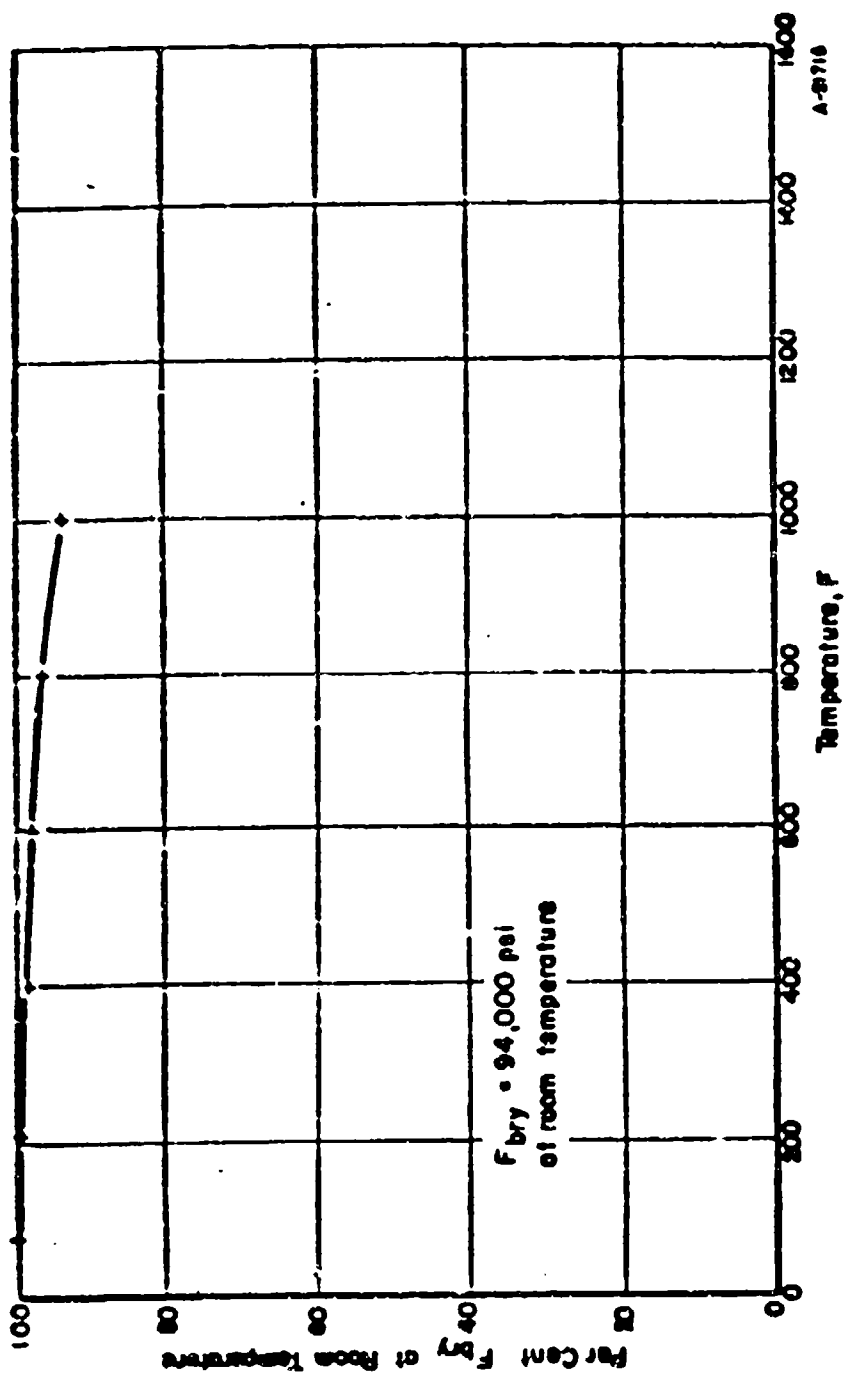


FIGURE 188. DESIGN CURVE FOR BEARING YIELD STRENGTH (F_{bry}) OF 19-9DX (AMS-5538) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 207.

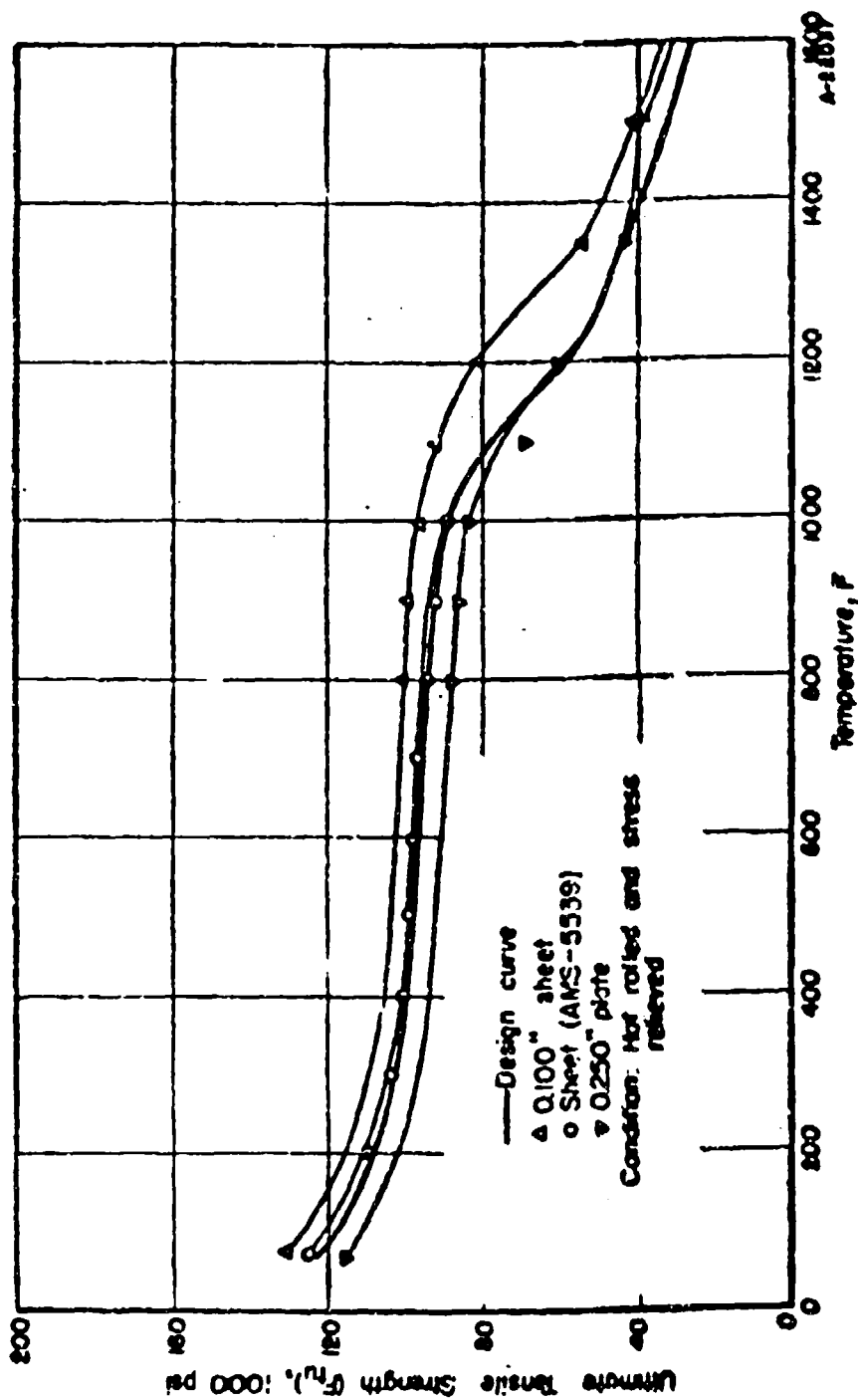


FIGURE 189. TENSILE STRENGTH (F_u) OF 19-9DX (AMS-5539) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 207, 241.

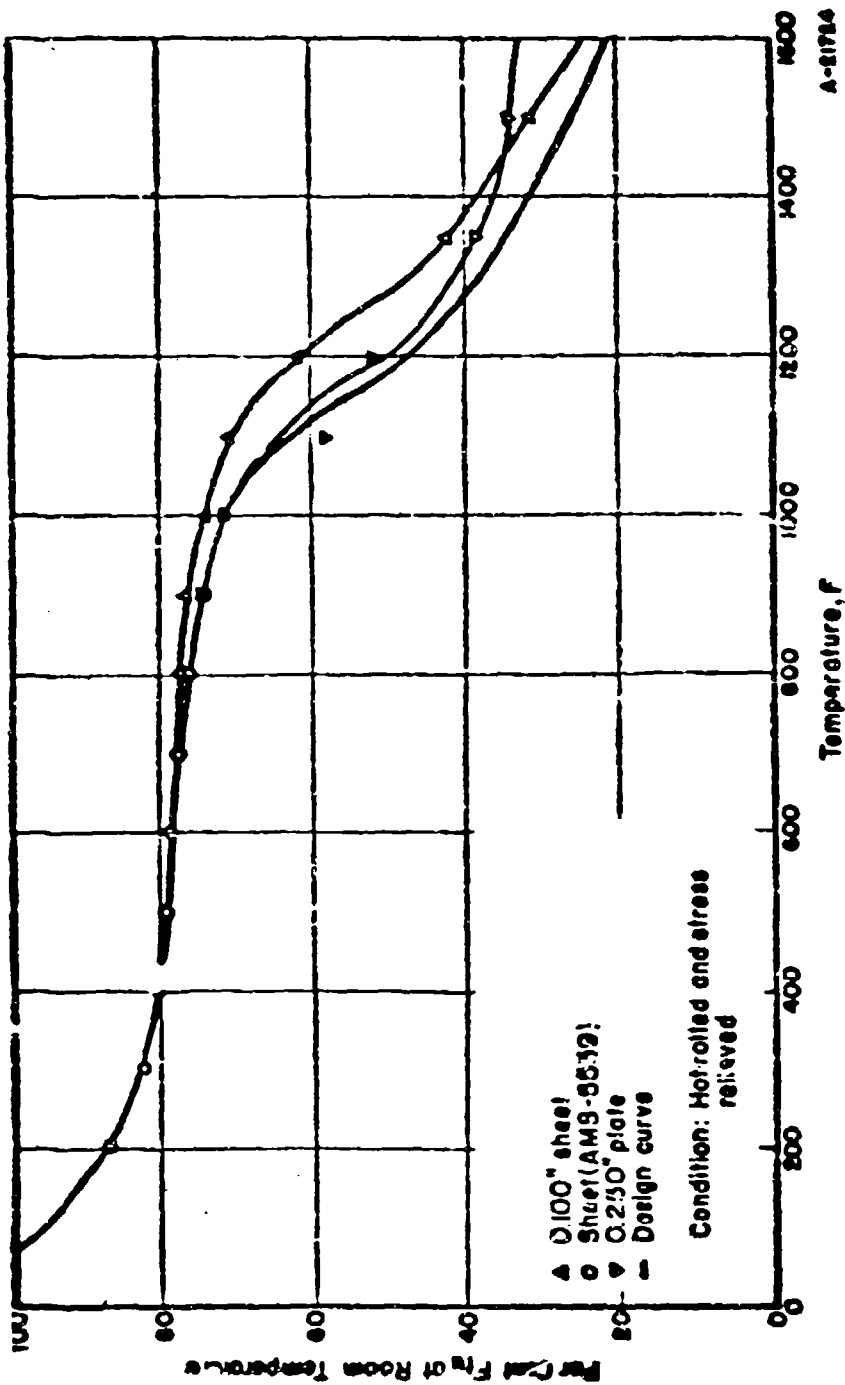


FIGURE 190. TENSILE STRENGTH (F_m) EXPRESSED AS A PERCENTAGE OF ROOM-TEMPERATURE TENSILE STRENGTH OF 19-9DX (AMS-5539) STAIN-LESS STEEL AT ELEVATED TEMPERATURE
Ref. 207, 241.

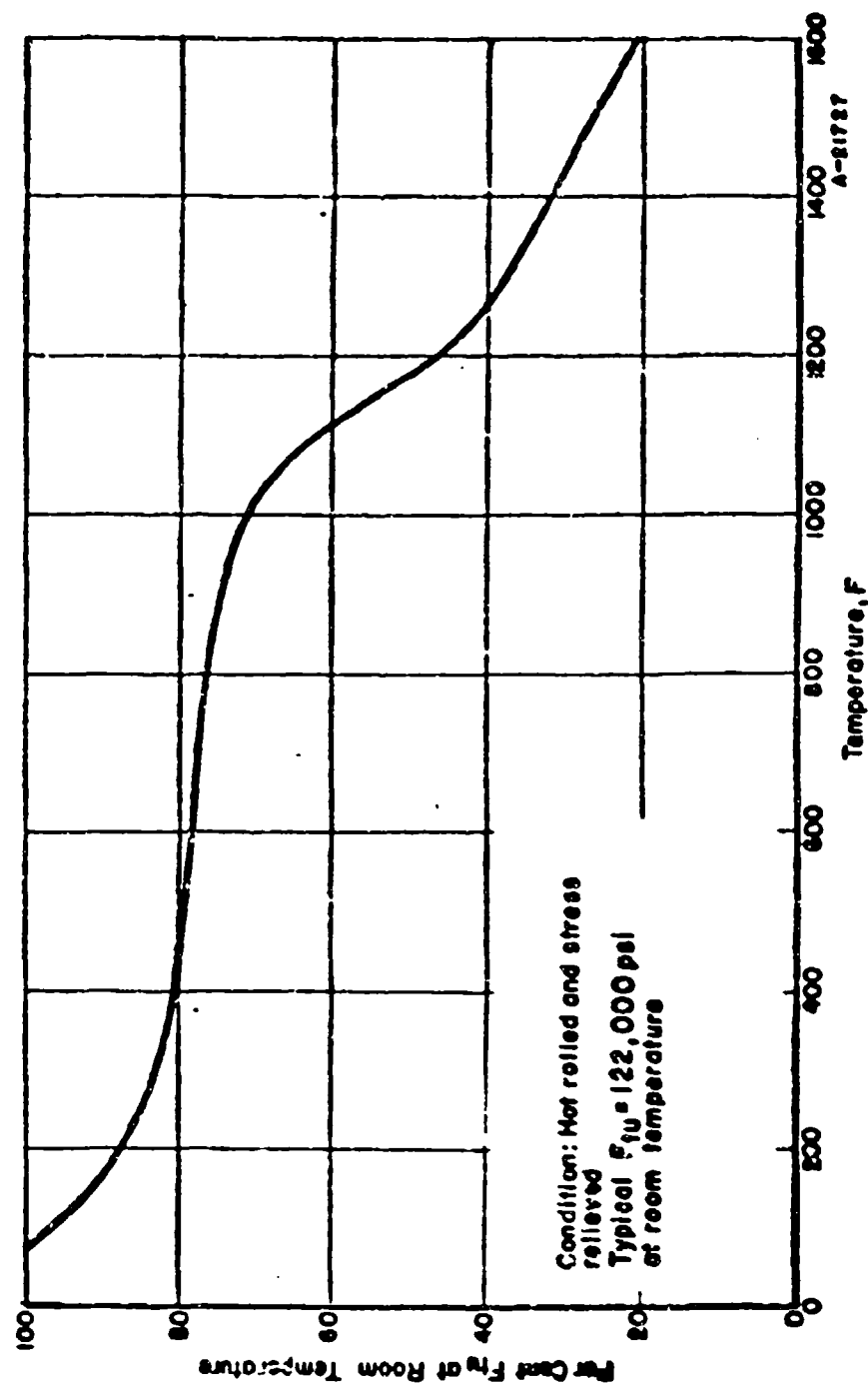


FIGURE 191. DESIGN CURVE FOR TENSILE STRENGTH (F_u) OF 19-9DX (AMS-5539) STAINLESS STEEL AT ELEVATED TEMPERATURE

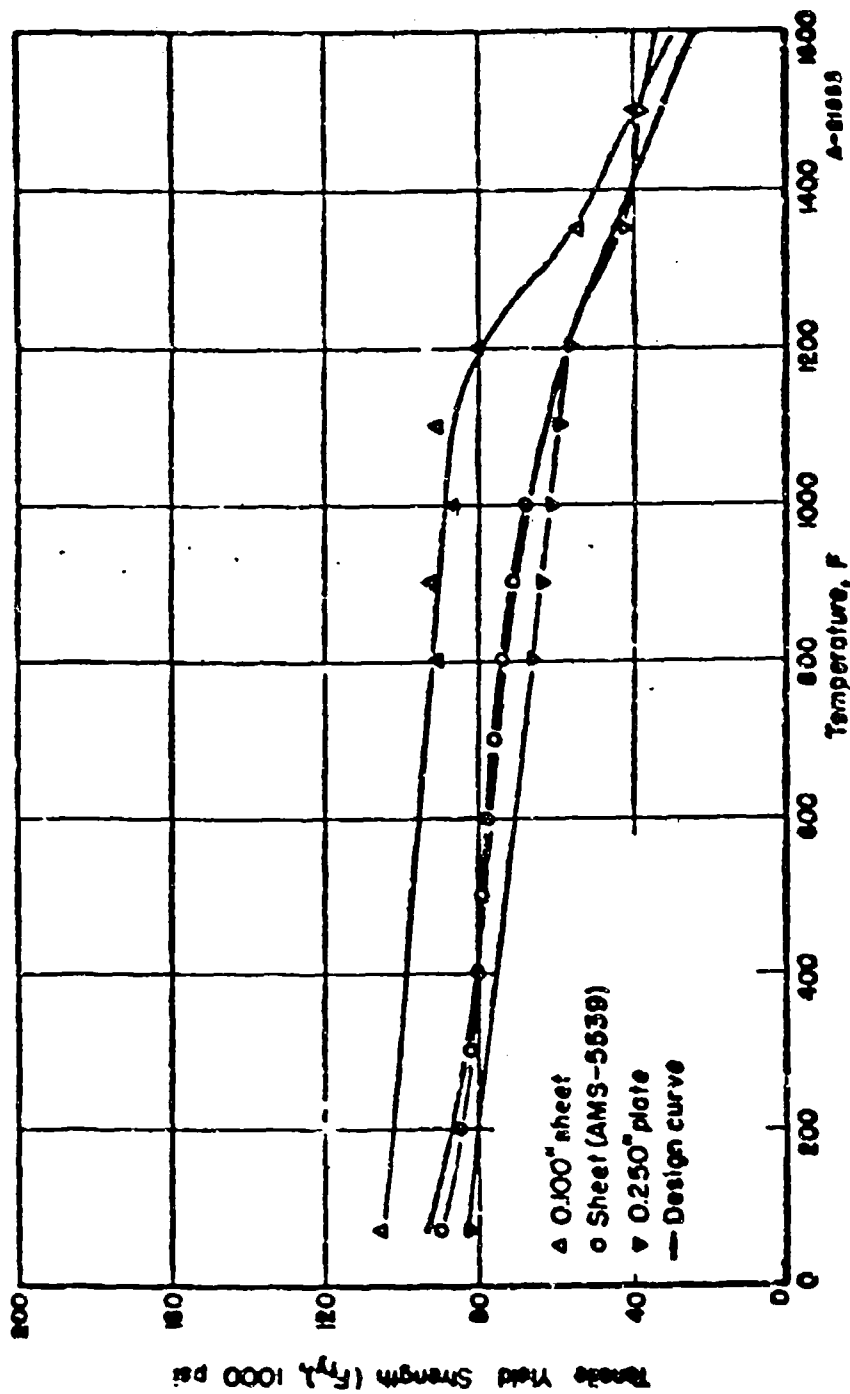


FIGURE 192. TENSILE YIELD STRENGTH (F_y) OF 19-9DX (AMS-5539) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 207, 241.

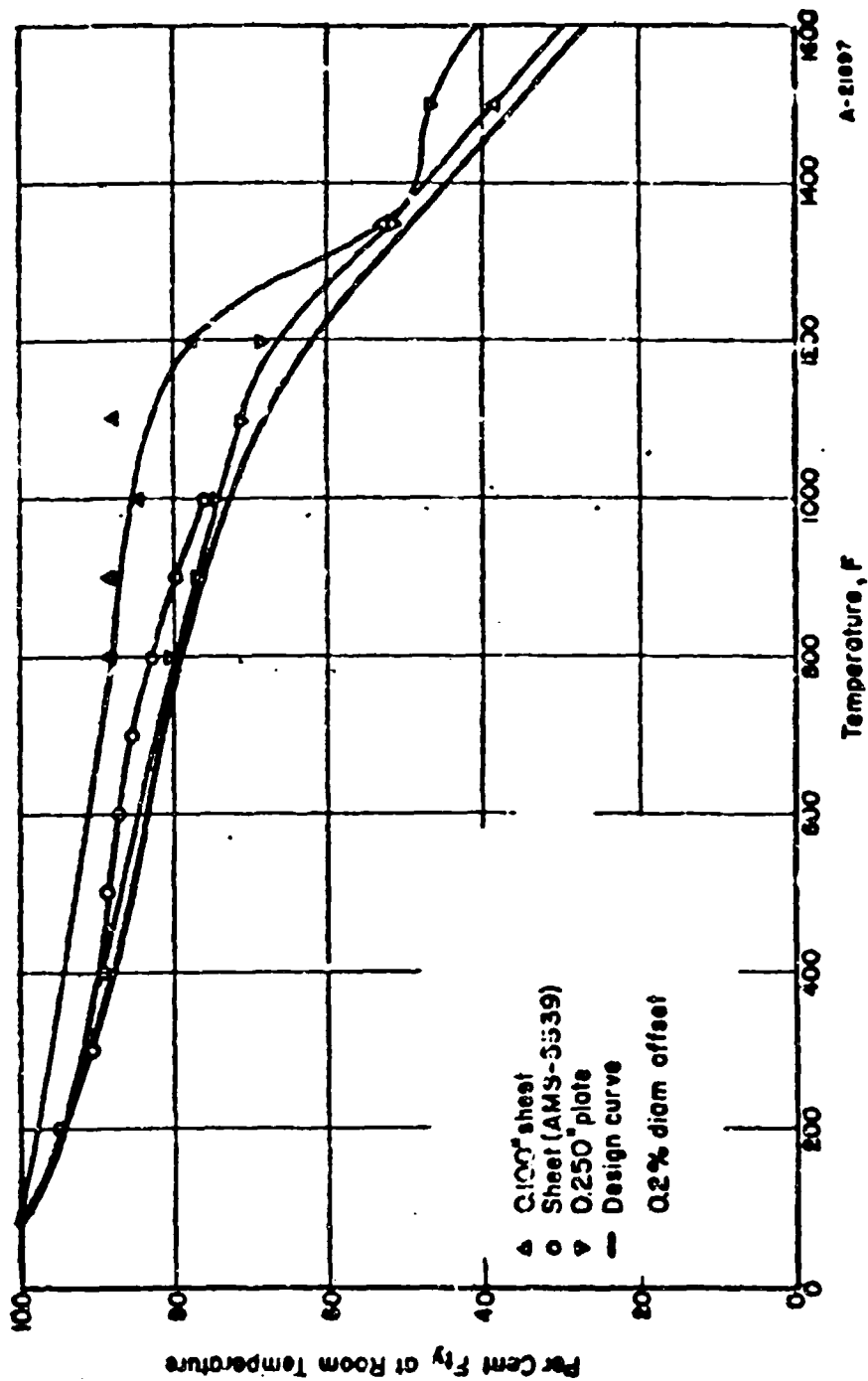


FIGURE 193. TENSILE YIELD STRENGTH (F_y) EXPRESSED AS A PERCENTAGE OF ROOM-TEMPERATURE TENSILE YIELD STRENGTH OF 19-9DX (AMS-5539) STAIN-LESS STEEL AT ELEVATED TEMPERATURE

Ref. 207, 241.

A-21897

5 34 357-55 11 207A

512

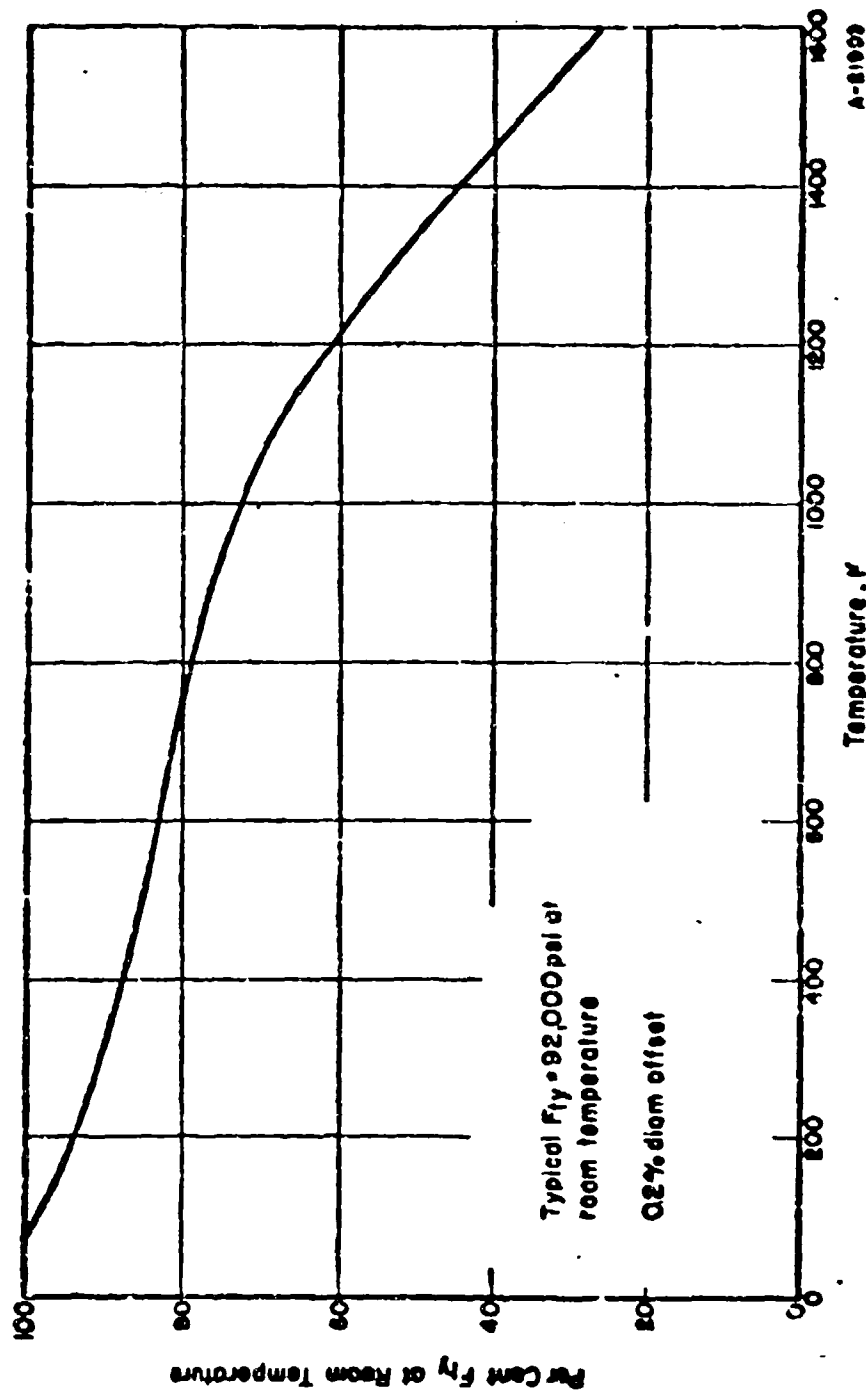


FIGURE 144. DESIGN CURVE FOR TENSILE YIELD STRENGTH (F_{ty}) OF 19-9DX (AMS-5539) STAINLESS STEEL AT ELEVATED TEMPERATURE

512

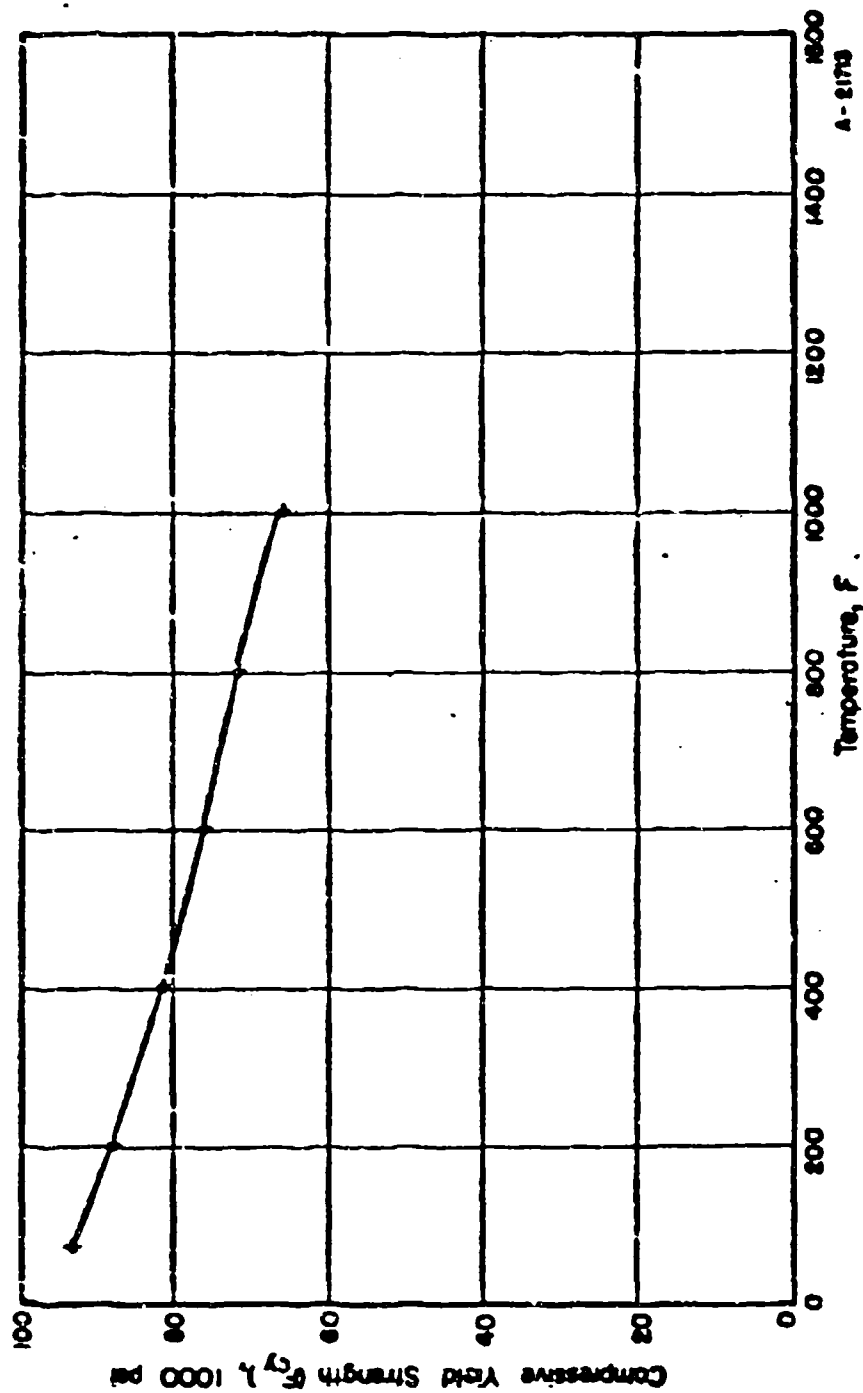


FIGURE 195. COMPRESSIVE YIELD STRENGTH (F_{cy}) OF 19-9DX (AMS-5539) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 207.

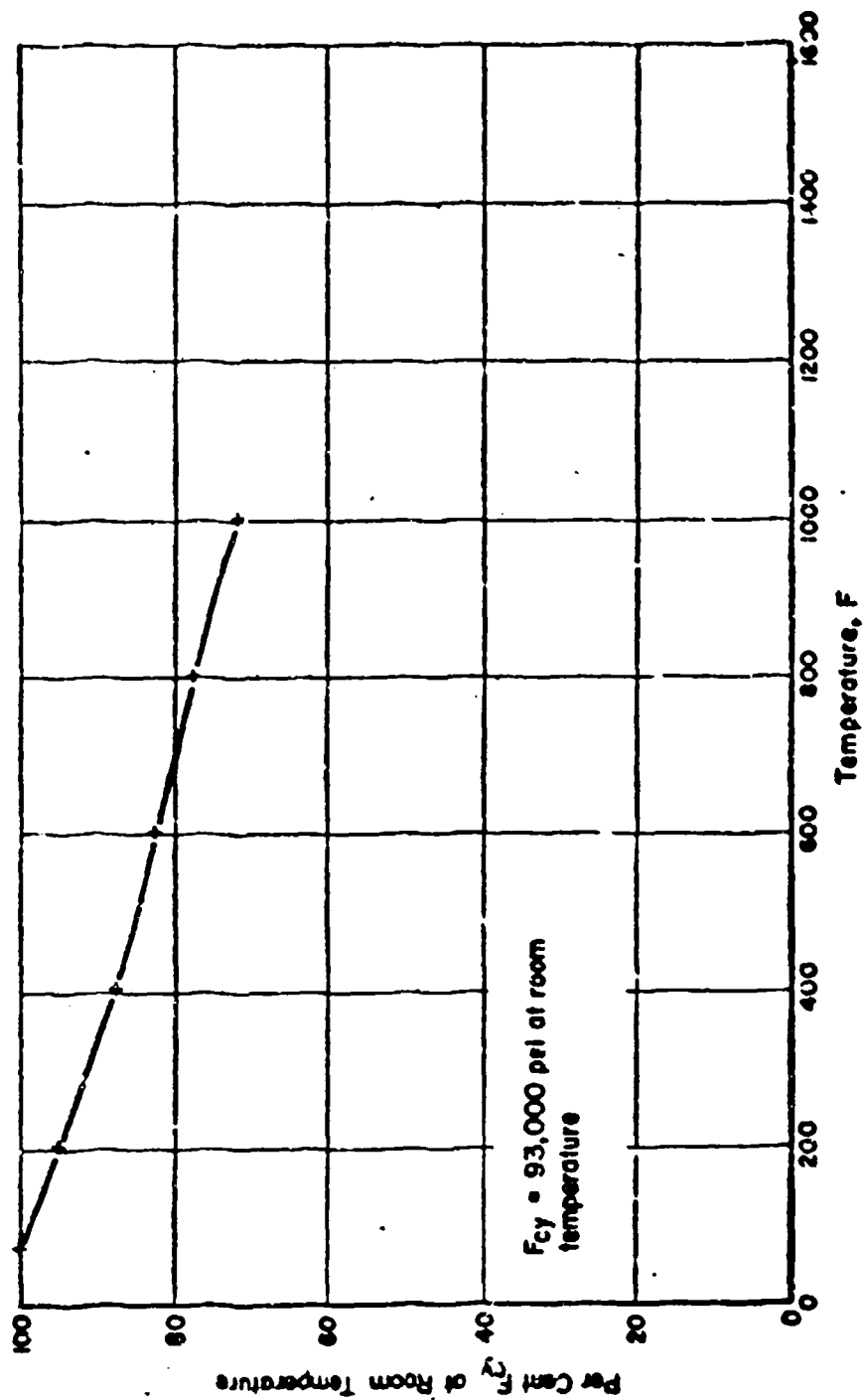


FIGURE 196. DESIGN CURVE FOR COMPRESSIVE YIELD STRENGTH (F_{cy}) OF 19-9DX (AMS-5537) STAINLESS STEEL AT ELEVATED TEMPERATURE

Ref. 207.

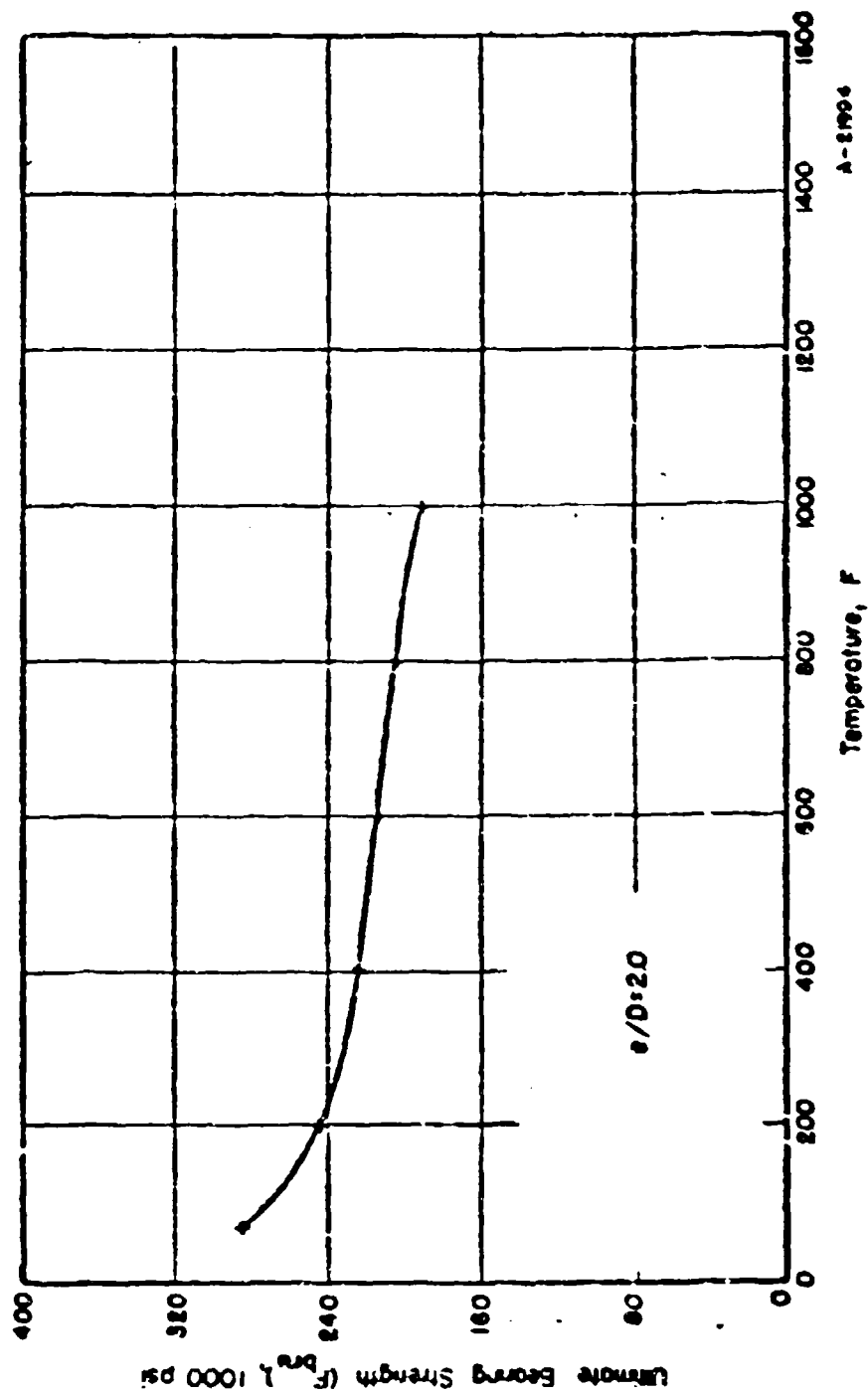


FIGURE 197. BEARING STRENGTH (F_{bru}) OF 19-9DX (AMS-5539) STAINLESS STEEL AT ELEVATED TEMPERATURE

A-21966

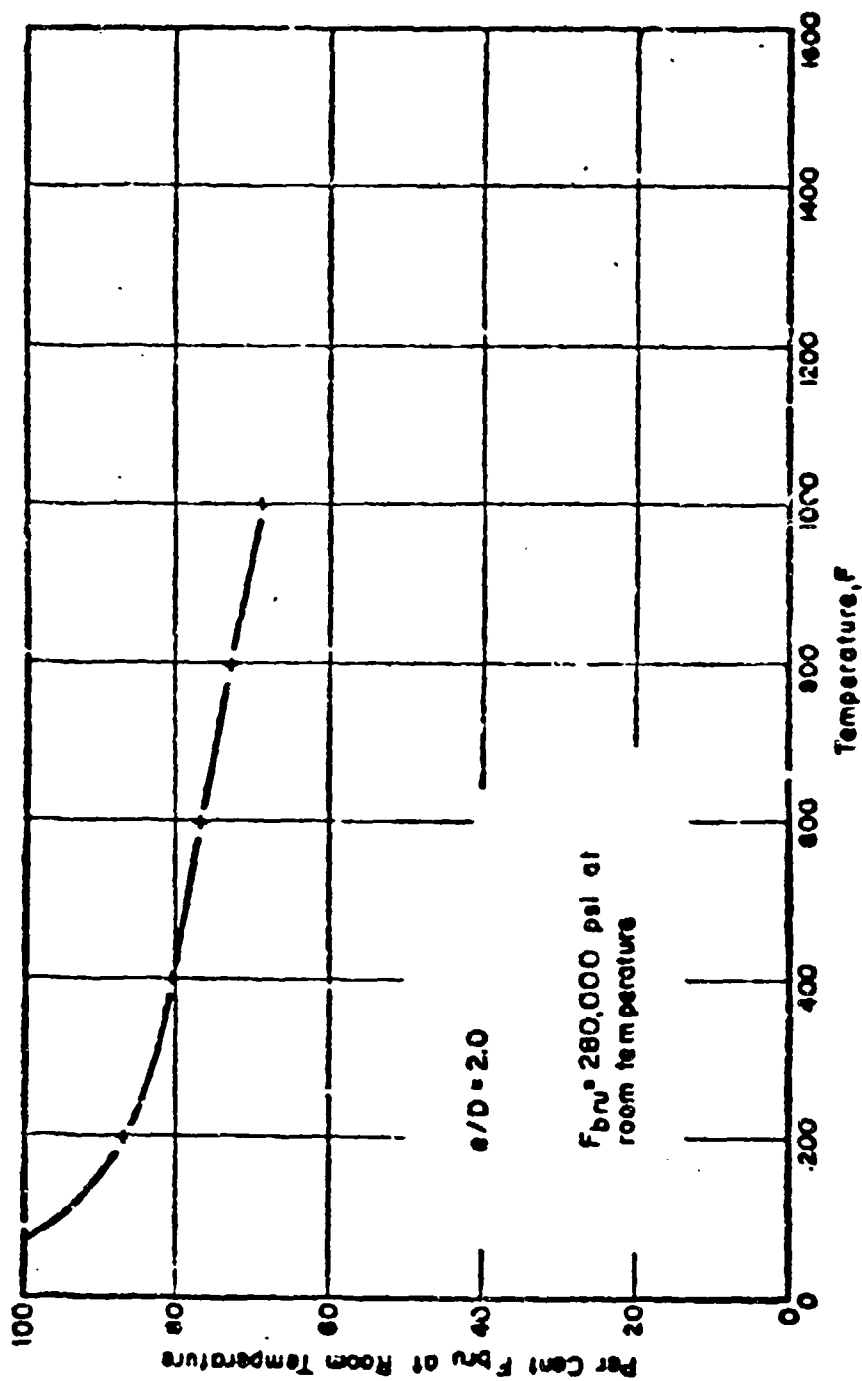


FIGURE 198. DESIGN CURVE FOR BEARING STRENGTH (F_{bru}) OF 19-9DX (AMS-5539) STAINLESS STEEL AT ELEVATED TEMPERATURE

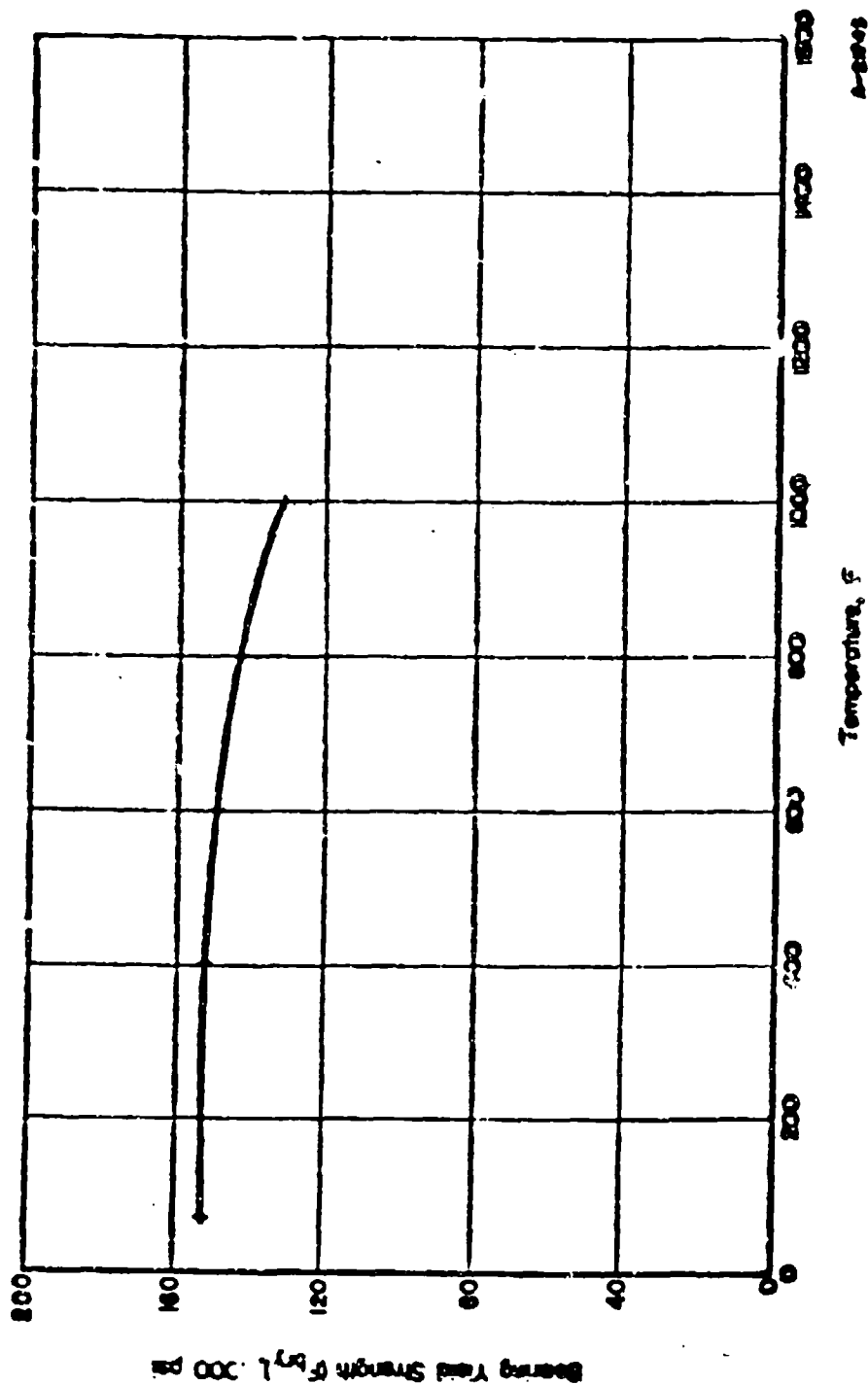


FIGURE 19. BEARING YIELD STRENGTH ($F_{0.2}$) OF 19-9DX (AMS-5539) STAINLESS STEEL AT ELEVATED TEMPERATURE

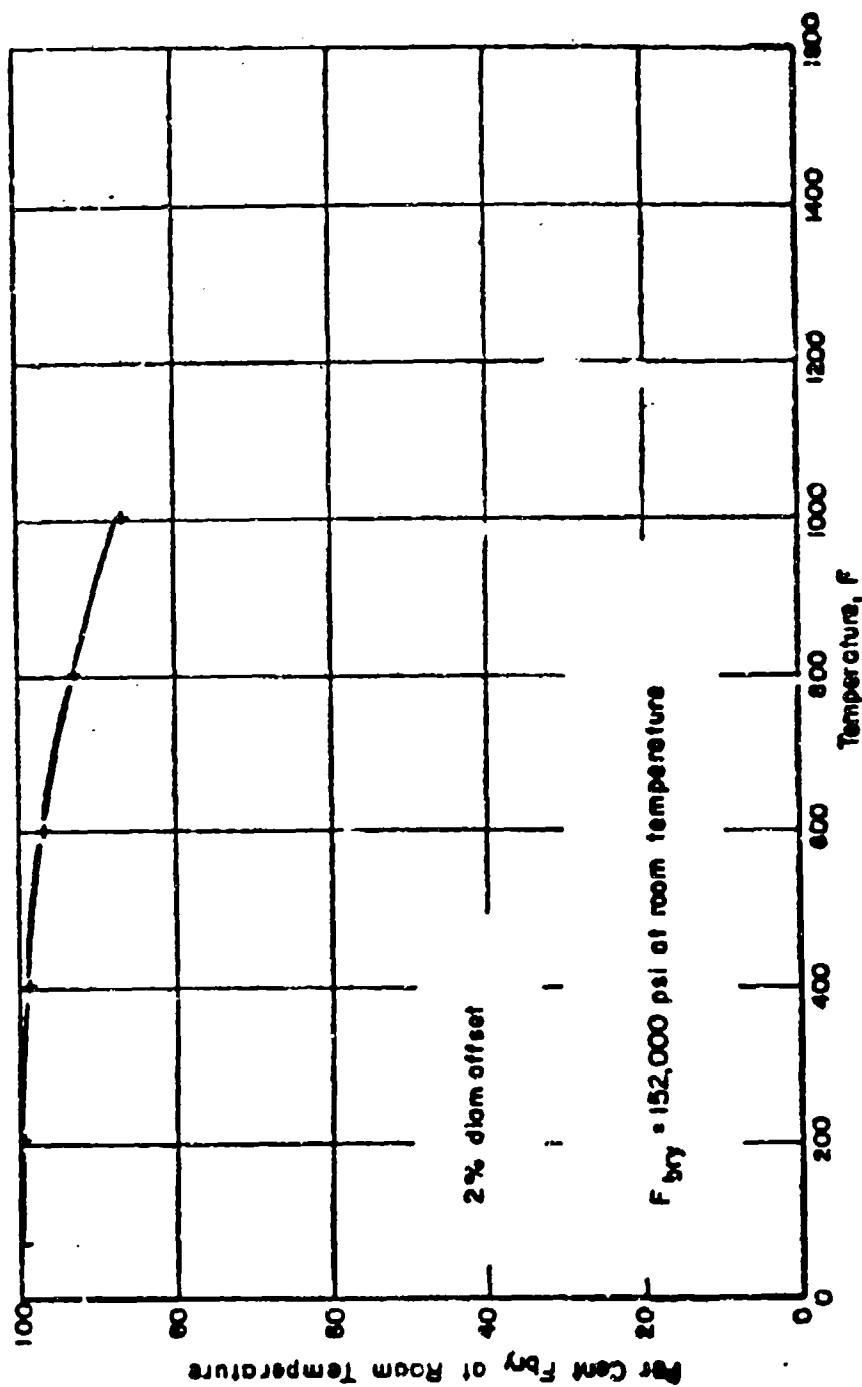


FIGURE 200. DESIGN CURVE FOR BEARING YIELD STRENGTH (F_{bry}) OF 19-9DX (AMS-5539) STAINLESS STEEL AT ELEVATED TEMPERATURE

A-286 ALLOY

The A-286 is an austenitic alloy which has been made heat treatable by the addition of titanium. The typical chemical composition of A-286 is shown in Table 14.

TABLE 14. TYPICAL CHEMICAL
COMPOSITION OF
A-286 ALLOY

Element	Weight Per Cent
Carbon	0.045
Manganese	1.35
Silicon	0.95
Nickel	26.00
Chromium	15.50
Molybdenum	1.25
Titanium	1.95
Vanadium	0.32
Aluminum	0.20
Iron	Balance

Alloy A-286 is a precipitation-hardening alloy that develops its optimum properties by solution treating at 1800 F, followed by rapid cooling (oil quenching for large sections and air cooling for thin sections, such as sheet), and finally aging at 1325 F for a minimum time of 12 hours. The aging treatment develops the strength of A-286 by random formation of a fine precipitate in the austenitic matrix.

The short-time, elevated-temperature properties of A-286 are shown in the following curves:

- (1) Tensile properties, Figures 201 through 204
- (2) Modulus of elasticity, Figures 205 and 207
- (3) Poisson's ratio, Figure 206
- (4) Stress-strain curves, Figure 208

No compressive, shear, or bearing data were available on A-286.

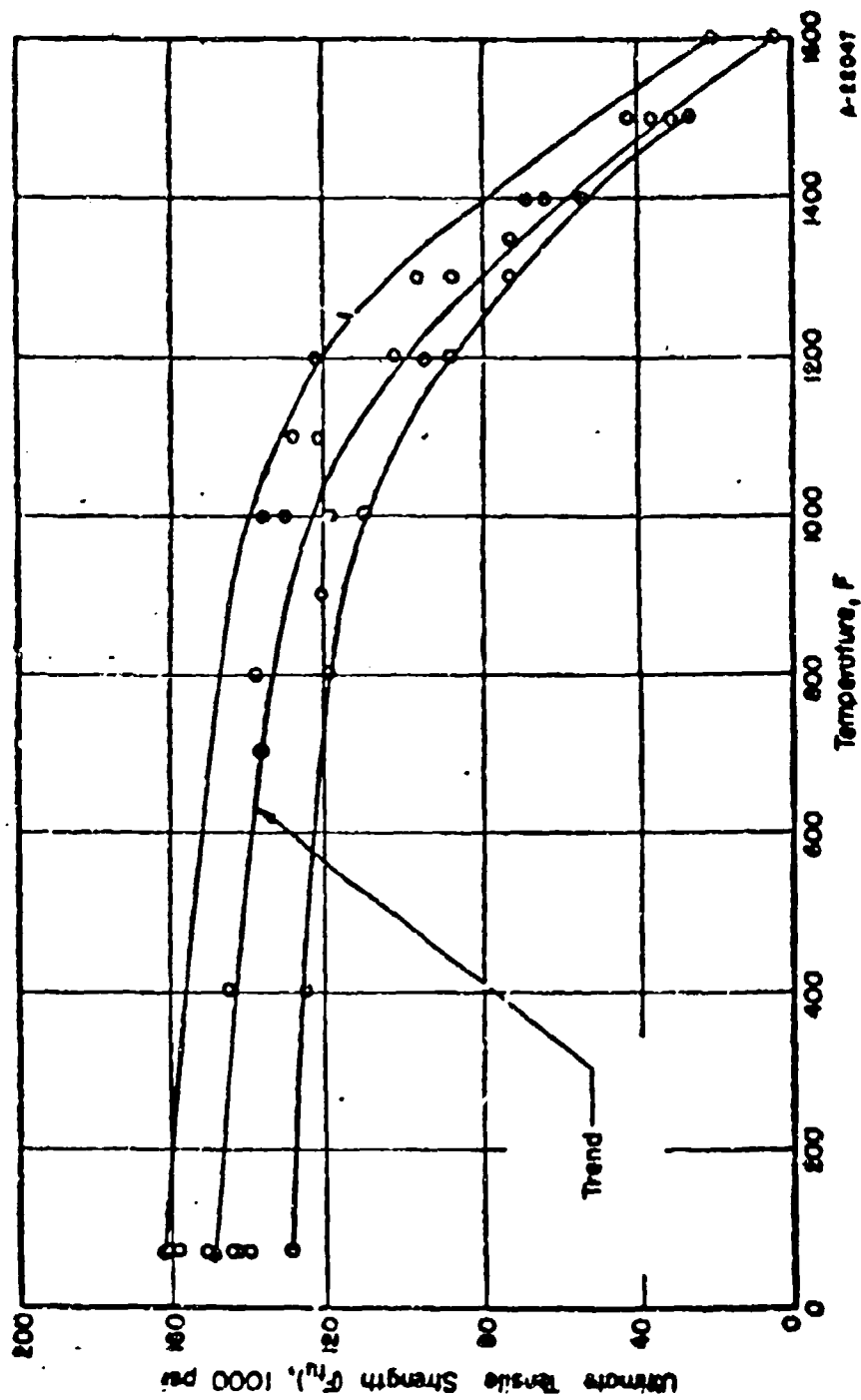


FIGURE 201. TENSILE STRENGTH (F_{tu}) OF A-286 ALLOY AT ELEVATED TEMPERATURE

Ref. 29, 76, 86, 207, 215.

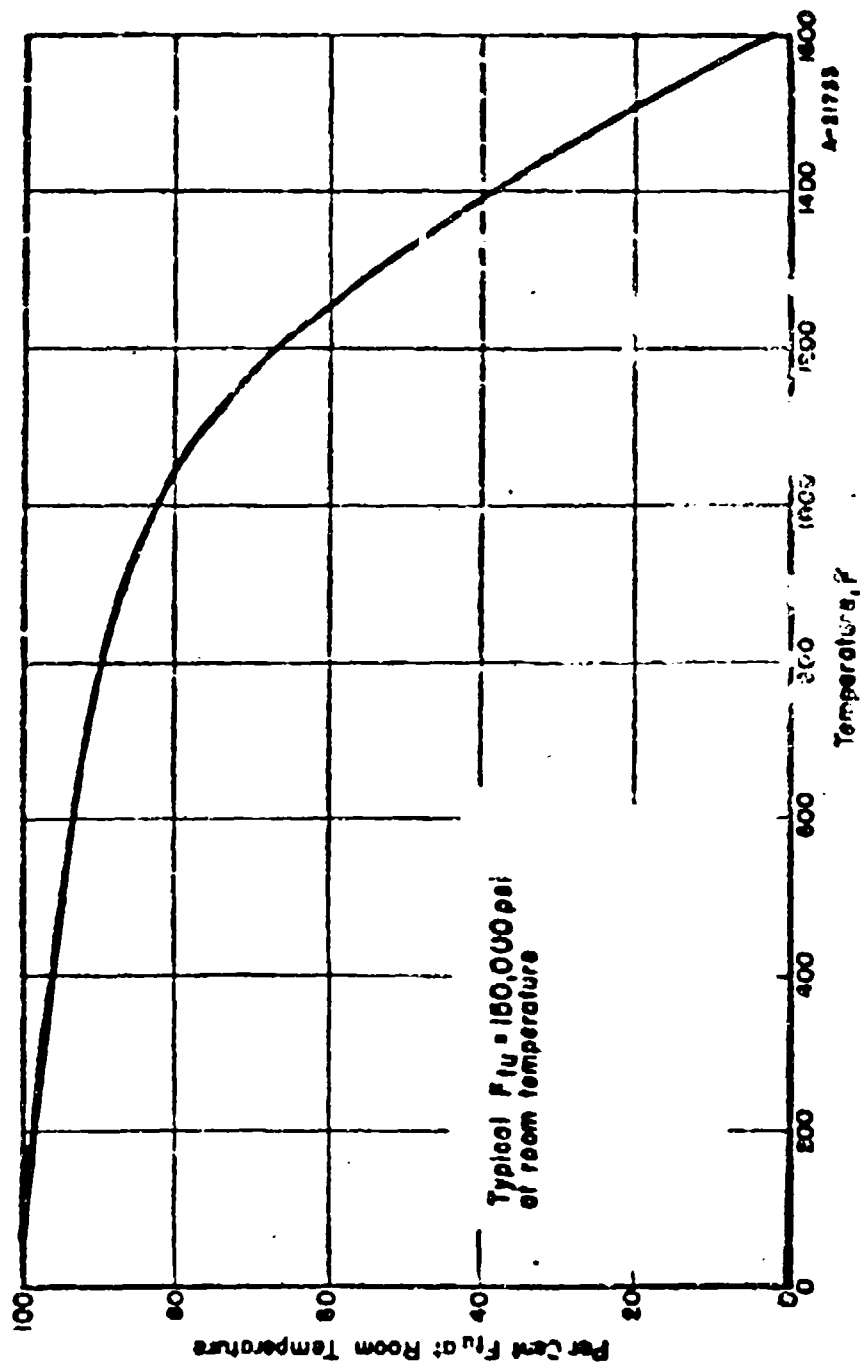


FIGURE 202. DESIGN CURVE FOR TENSILE STRENGTH (F_{tu}) OF 286 ALLOY AT ELEVATED TEMPERATURE

Ref. 29, 76, 86, 207, 215.

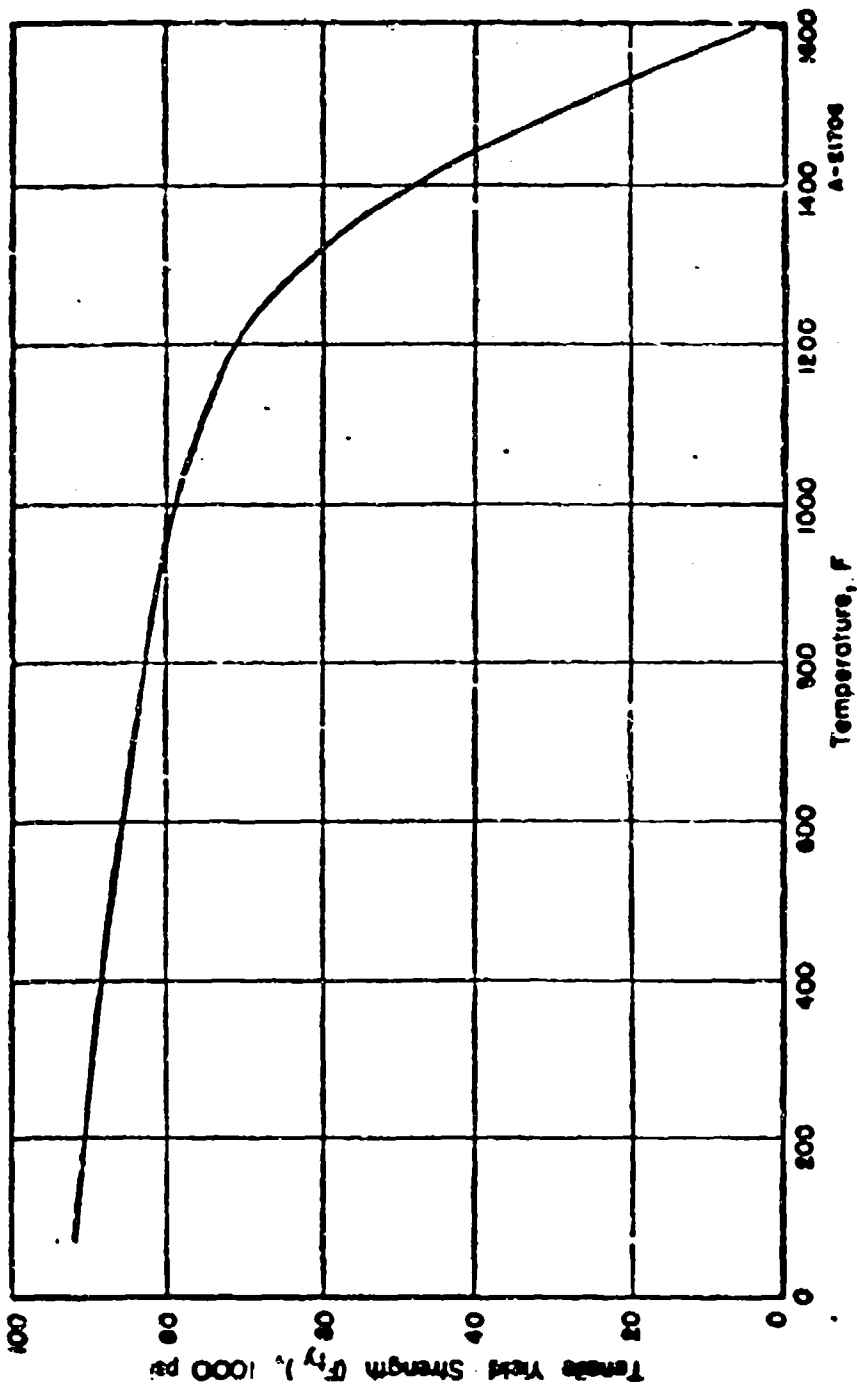


FIGURE 203. TENSILE YIELD STRENGTH (F_{ty}) OF A-286 ALLOY AT ELEVATED TEMPERATURE

Ref. 29.

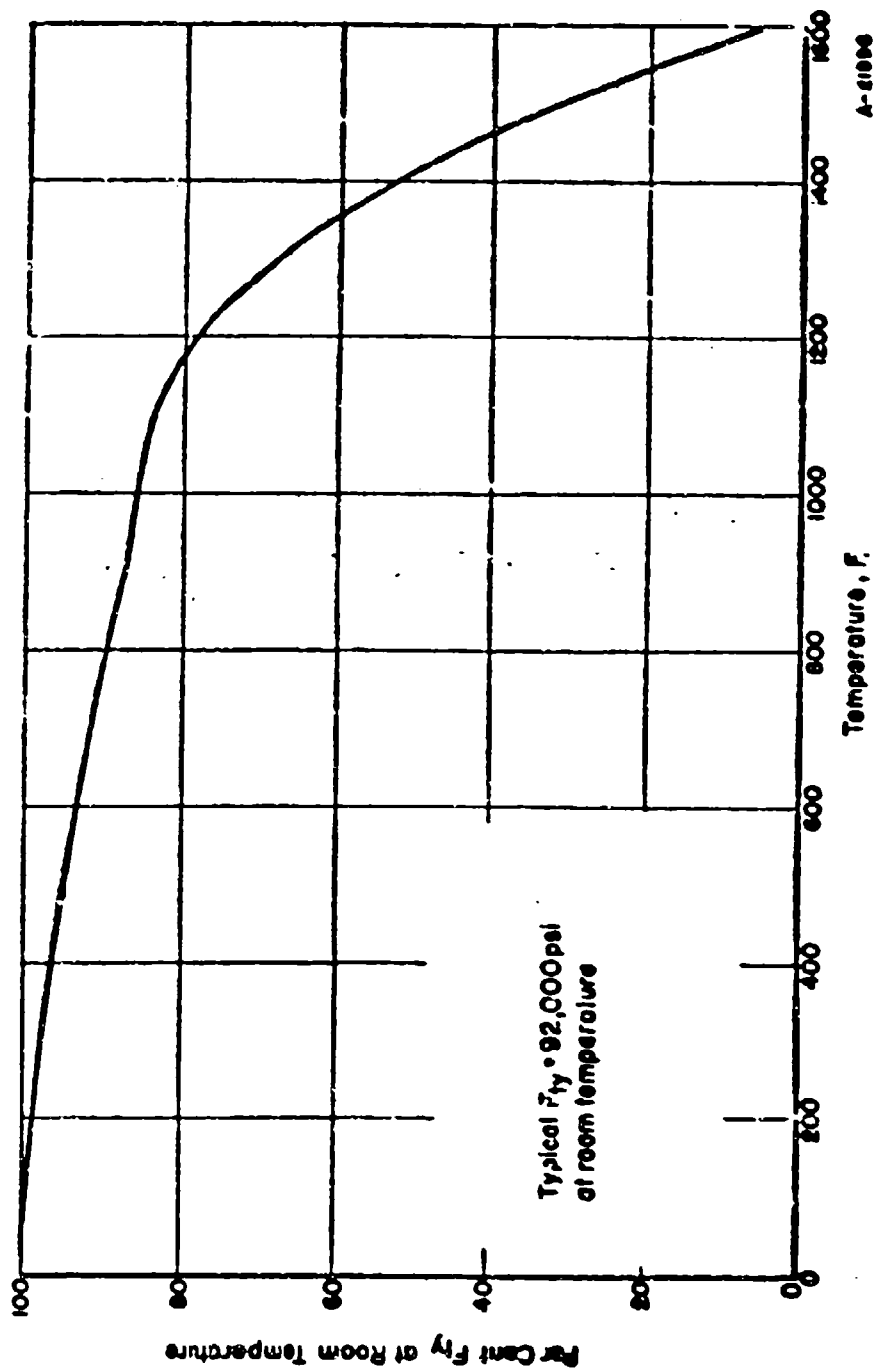


FIGURE 204. DESIGN CURVE FOR TENSILE YIELD STRENGTH (F_{ty}) OF A-286 ALLOY AT ELEVATED TEMPERATURE

Ref. 29.

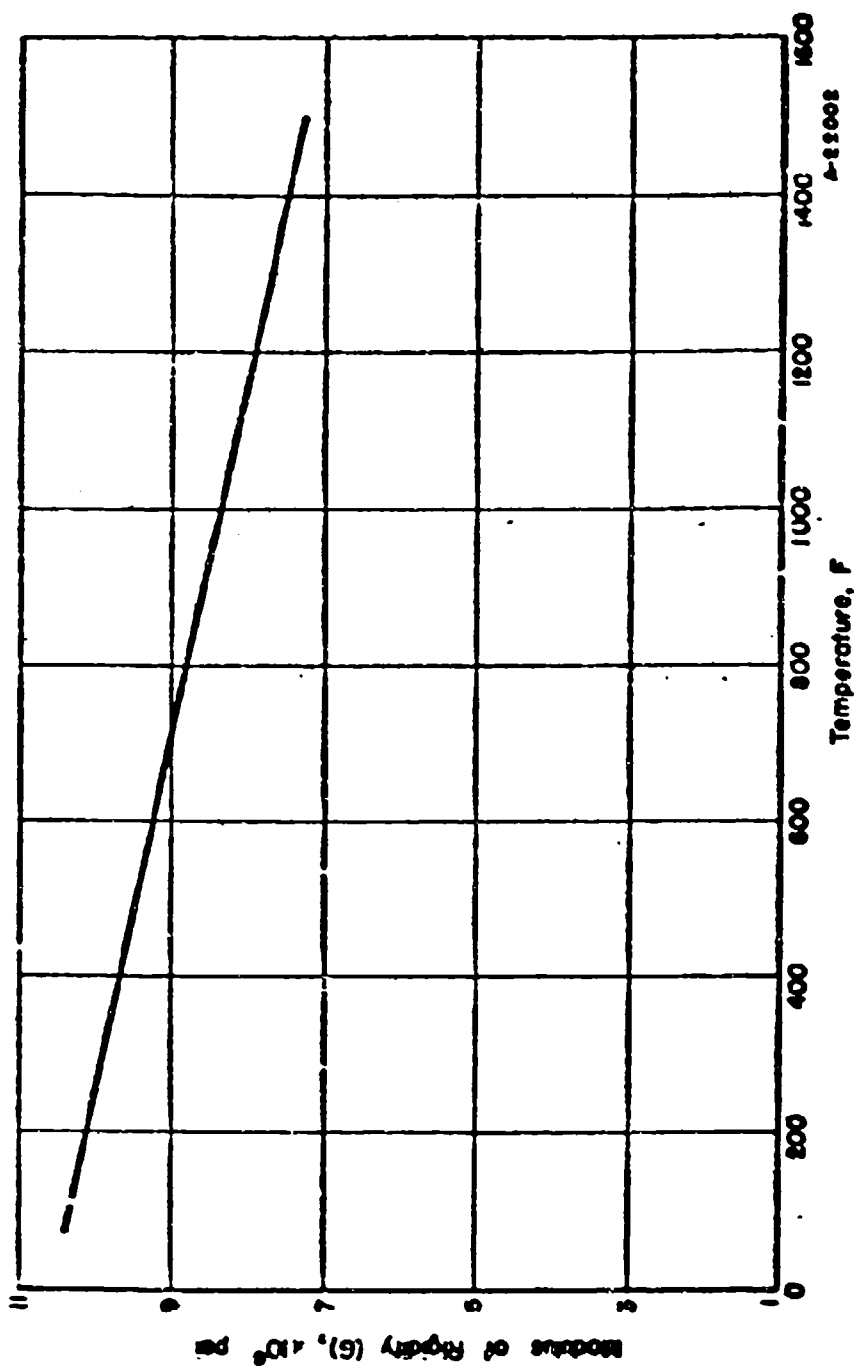


FIGURE 205. EFFECT OF ELEVATED TEMPERATURE ON THE MODULUS OF RIGIDITY (G) OF A-286 ALLOY

Ref. 74.

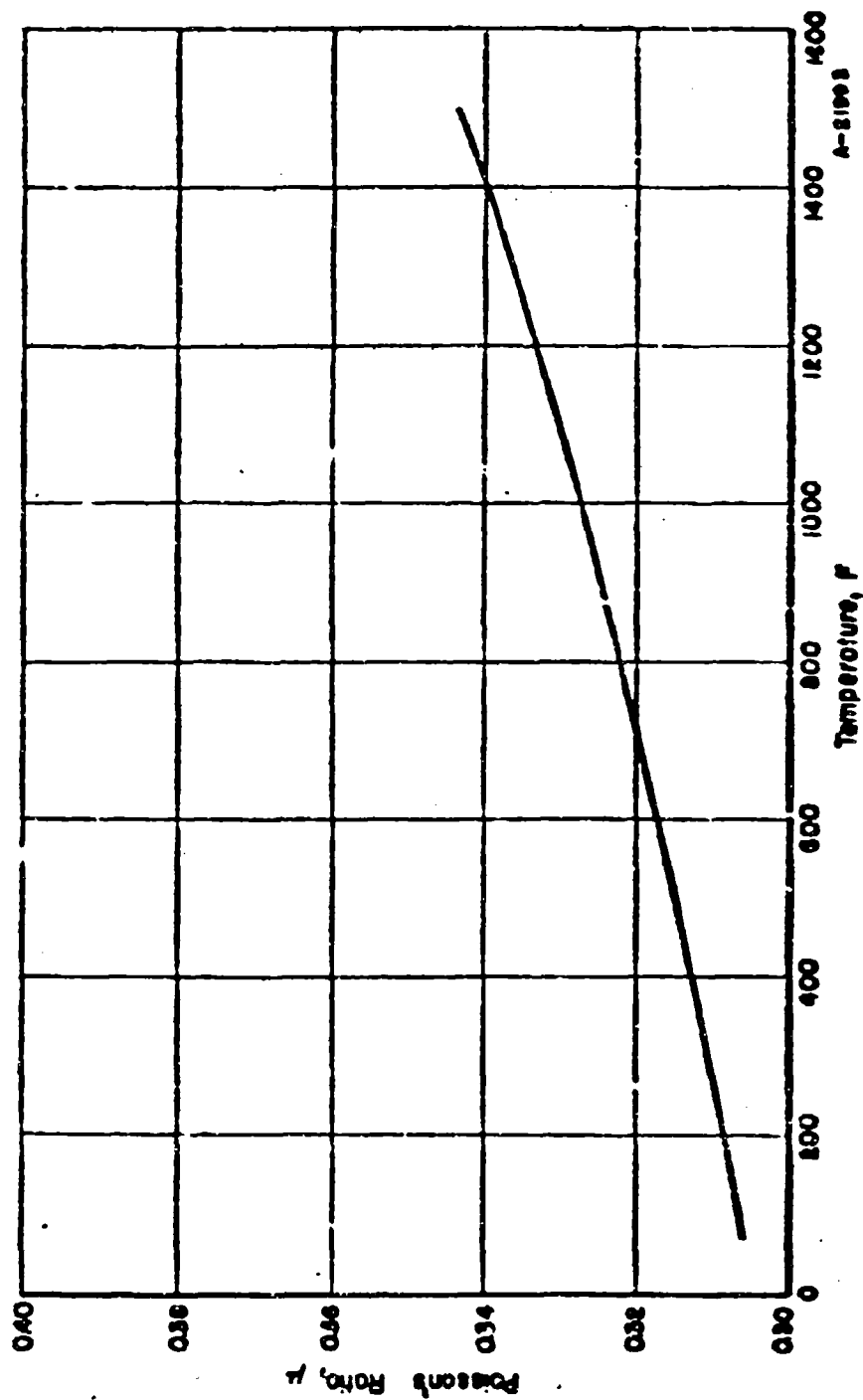


FIGURE 206. EFFECT OF ELEVATED TEMPERATURE ON POISSON'S RATIO (μ) OF A-286 ALLOY

Ref. 74.

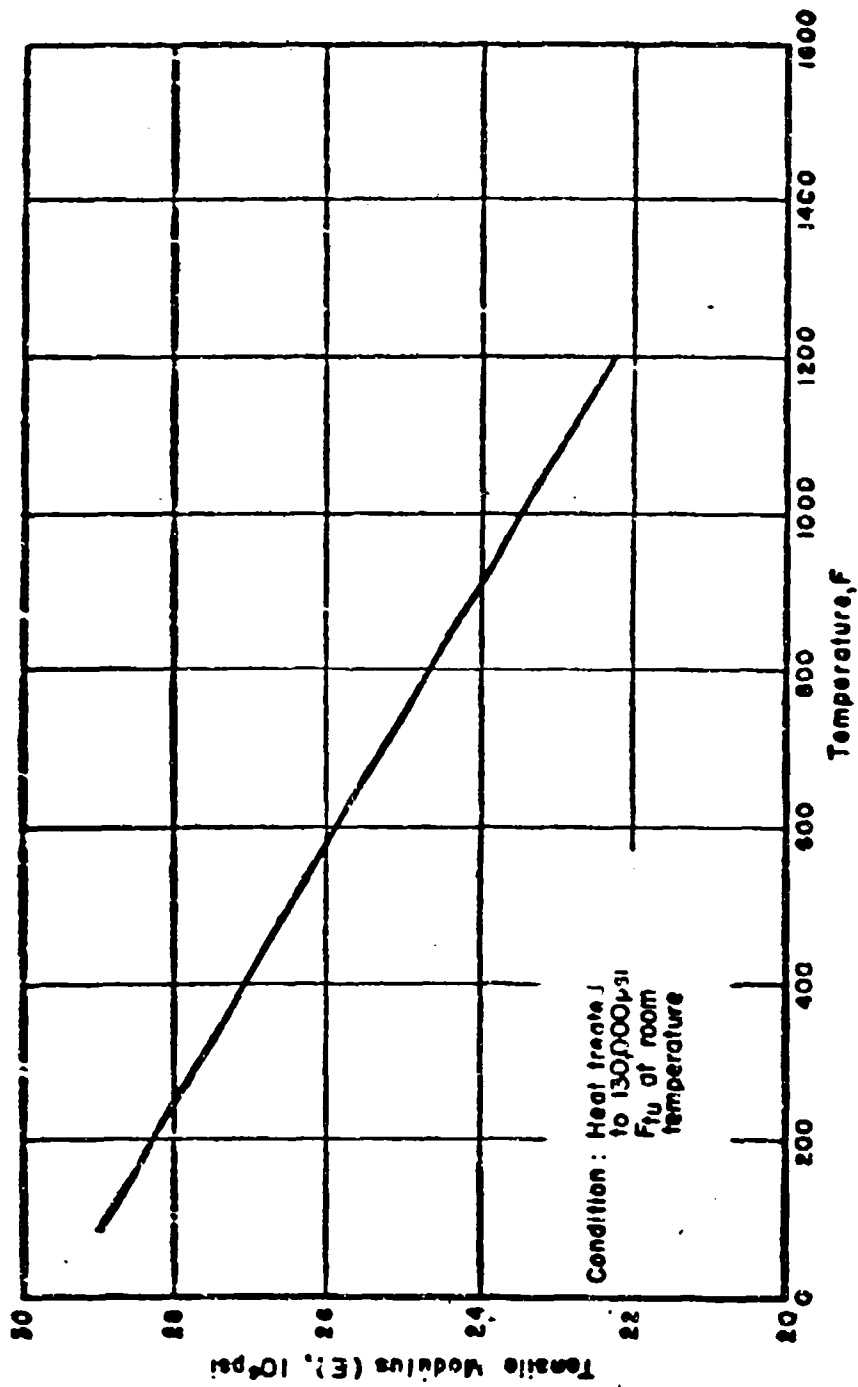


FIGURE 207. TENSILE MODULUS (E) OF A-286 ALLOY (SHEET) AT ELEVATED TEMPERATURE

Ref. 207, p 9-3-1-1.

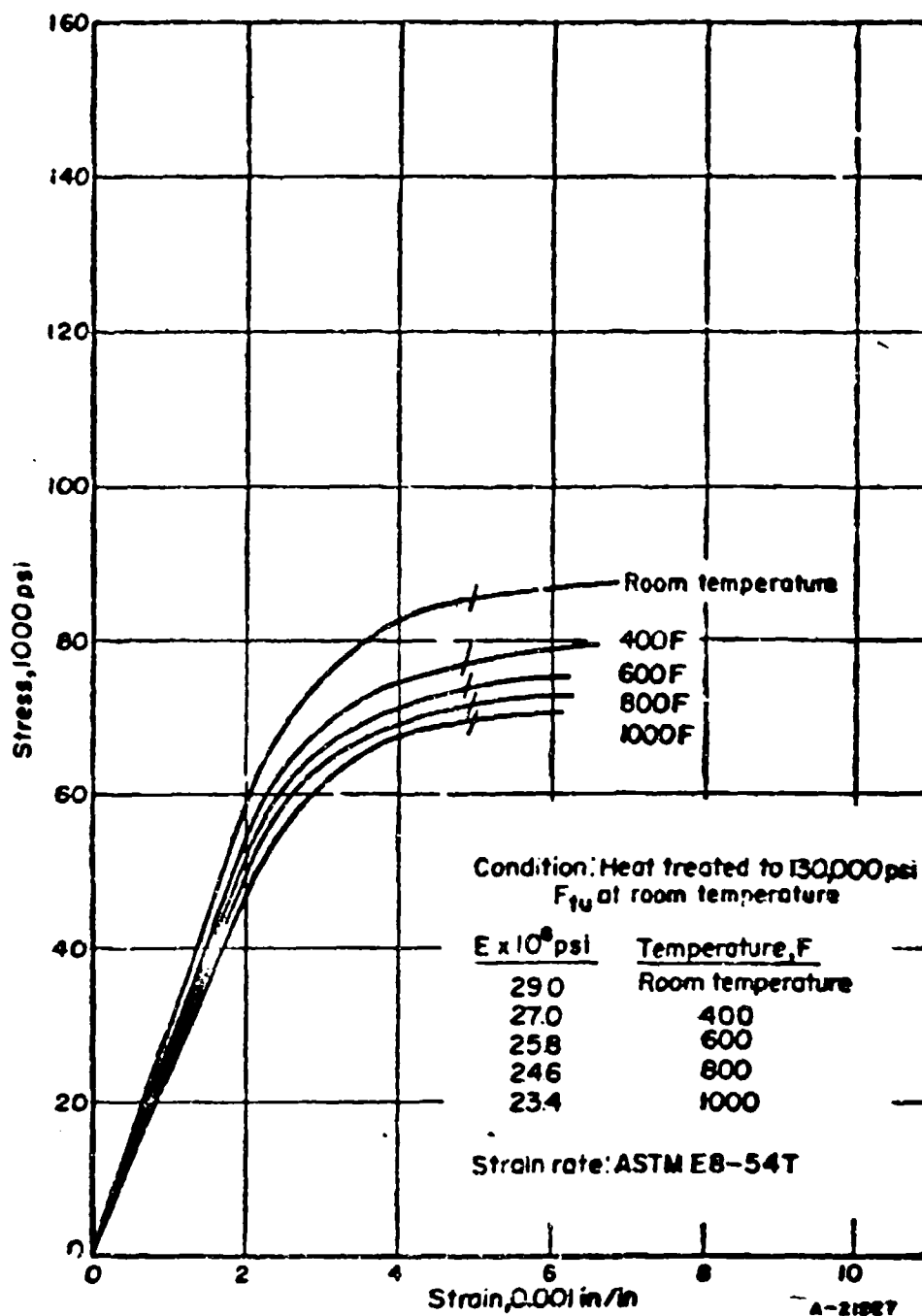


FIGURE 208. TENSILE STRESS-STRAIN CURVES FOR
A-286 ALLOY SHEET

Ref. 207.

INCONEL "X"
(MIL-N-7786) (AMS-5542D)

Inconel "X" is a wrought nickel-base alloy which is highly resistant to chemical corrosion and oxidation. Additions of titanium and aluminum render the alloy age-hardenable. The limiting chemical composition of Inconel "X" is given in Table 15.

TABLE 15. CHEMICAL COMPOSITION OF
INCONEL "X" (MIL-N-7786)
(AMS-5542D)

Element	Weight Per Cent
Nickel, minimum	70.0
Chromium	14-16
Iron	5-9
Titanium	2.25-2.75
Columbium + tantalum	0.7-1.2
Aluminum	0.4-1.0
Silicon, maximum	0.5
Manganese	0.3-1.0
Copper, maximum	0.2
Carbon, maximum	0.08
Sulfur, maximum	0.01

Two typical conditions for hot-rolled Inconel "X" are summarized below.

Fully Heat-Treated Hot-Rolled Rods

- (a) Solution treated at 2100 F for 4 hours and air-cooled
- (b) Aged at 1550 F for 24 hours and air cooled
- (c) Aged at 1300 F for 20 hours and air cooled.

Typical room-temperature properties for this condition are shown in Table 16.

TABLE 16. TYPICAL ROOM-TEMPERATURE
PROPERTIES OF FULLY HEAT-
TREATED HOT-ROLLED
INCONEL "X"

Property	
Ultimate tensile (F_{tu})	162,000 psi
Tensile yield (F_{ty})	92,000 psi
Elongation (e) in 2 inches	24 per cent
Reduction in area	30 per cent

Hot Rolled and Aged, Not
Solution Treated

(a) Aged at 1300 F for 20 hours.

Typical room-temperature properties for this condition are shown
in Table 17.

TABLE 17. TYPICAL ROOM-TEMPERATURE
PROPERTIES OF HOT-ROLLED
AND AGED INCONEL "X"

Property	
Ultimate tensile (F_{tu})	184,000 psi
Tensile yield (F_{ty})	132,000 psi
Elongation (e) in 2 inches	24 per cent
Reduction in area	37 per cent

Note: All high-temperature heat treating must be done in a sulfur-
free atmosphere.

Minimum mechanical properties of Inconel "X" as specified in AMS-
5542D are given in Table 18.

TABLE 18. MINIMUM MECHANICAL
PROPERTIES OF
INCONEL "X"
(AMS-5542D)

Property	
Ultimate tensile (F_{tu})	155,000 psi
Tensile yield (F_{ty})	100,000 psi
Elongation (e) in 2 inches	20 per cent

The short-time elevated-temperature properties of Inconel "X" are shown in the following curves:

- (1) Tensile properties, Figures 209 through 215
- (2) Compressive properties, Figures 216 and 217
- (3) Bearing properties, Figures 218 through 220
- (4) Shear properties, Figures 221 through 224
- (5) Modulus of elasticity, Figures 225 and 227
- (6) Poisson's ratio, Figure 226
- (7) Stress-strain curves, Figures 228 through 230

Data are available on Inconel "X" for all surveyed properties.

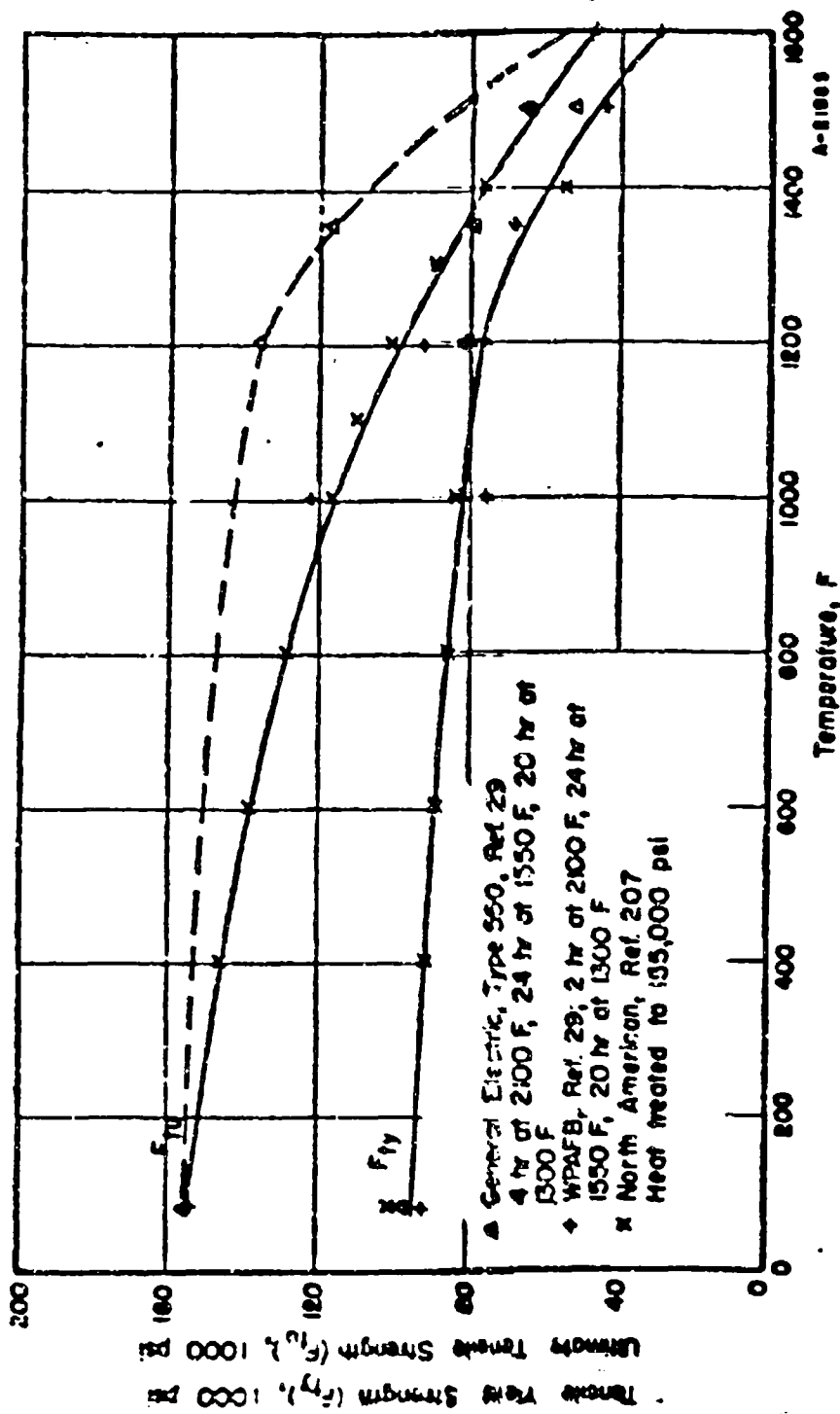
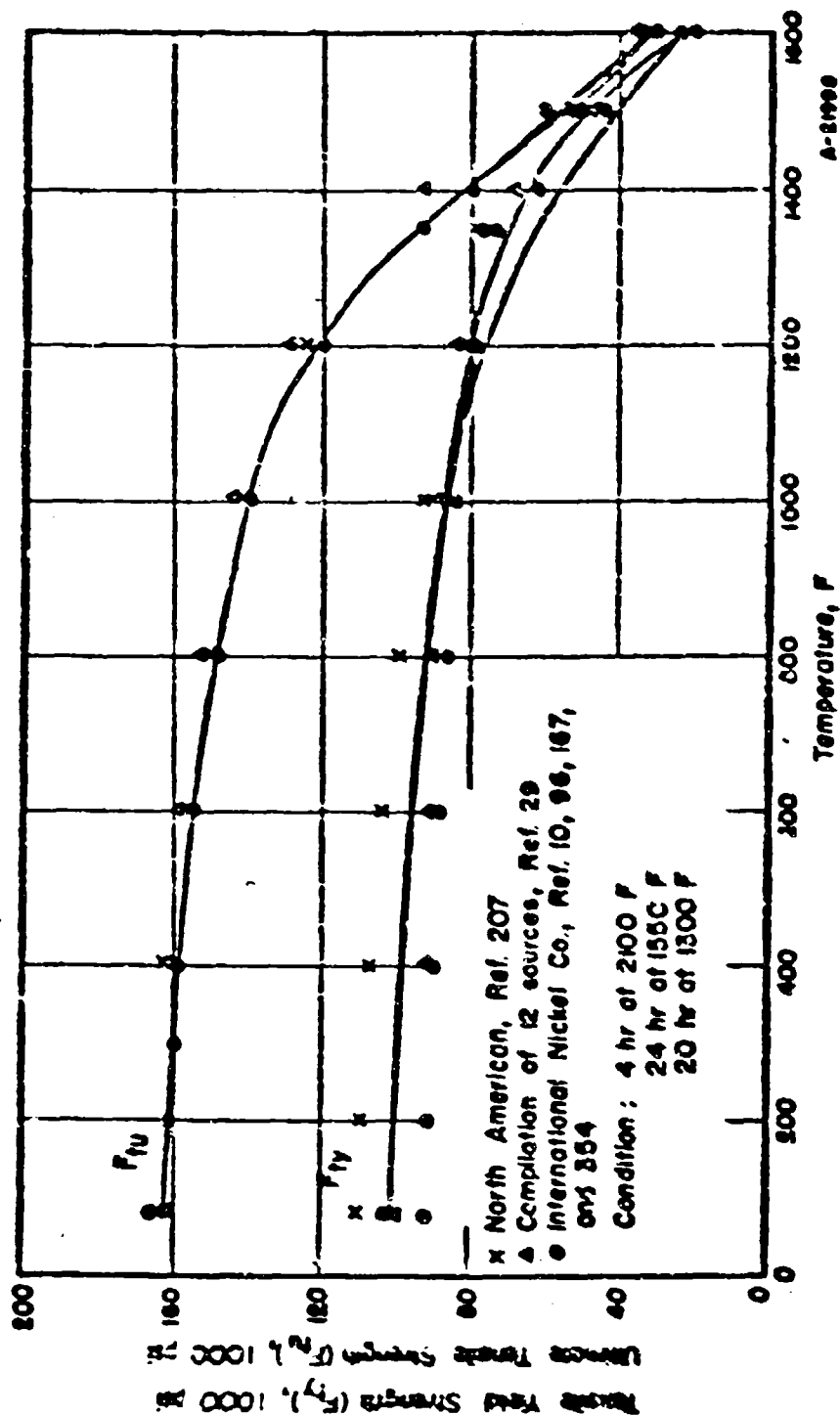


FIGURE 204. TENSILE AND TENSILE YIELD STRENGTHS (F_u AND F_y) OF INCONEL "X" AT ELEVATED TEMPERATURE



JRE 210. TENSILE AND TENSILE YIELD STRENGTHS (F_{tu} AND F_{ty}) OF INCONEL "X" AT ELEVATED TEMPERATURE

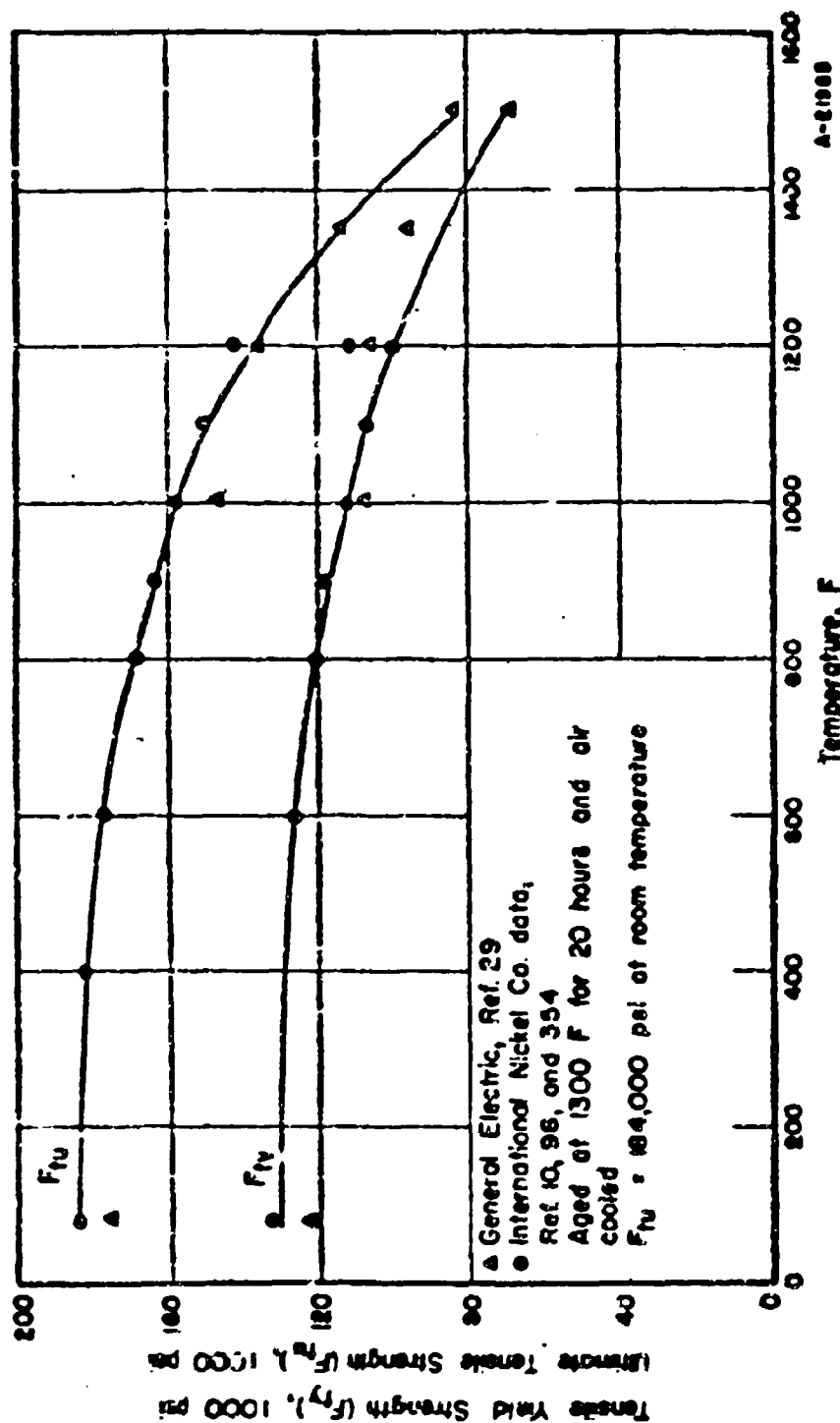


FIGURE 211. TENSILE AND TENSILE YIELD STRENGTHS (F_{tu} AND F_y) OF INCONEL "X" AT ELEVATED TEMPERATURE

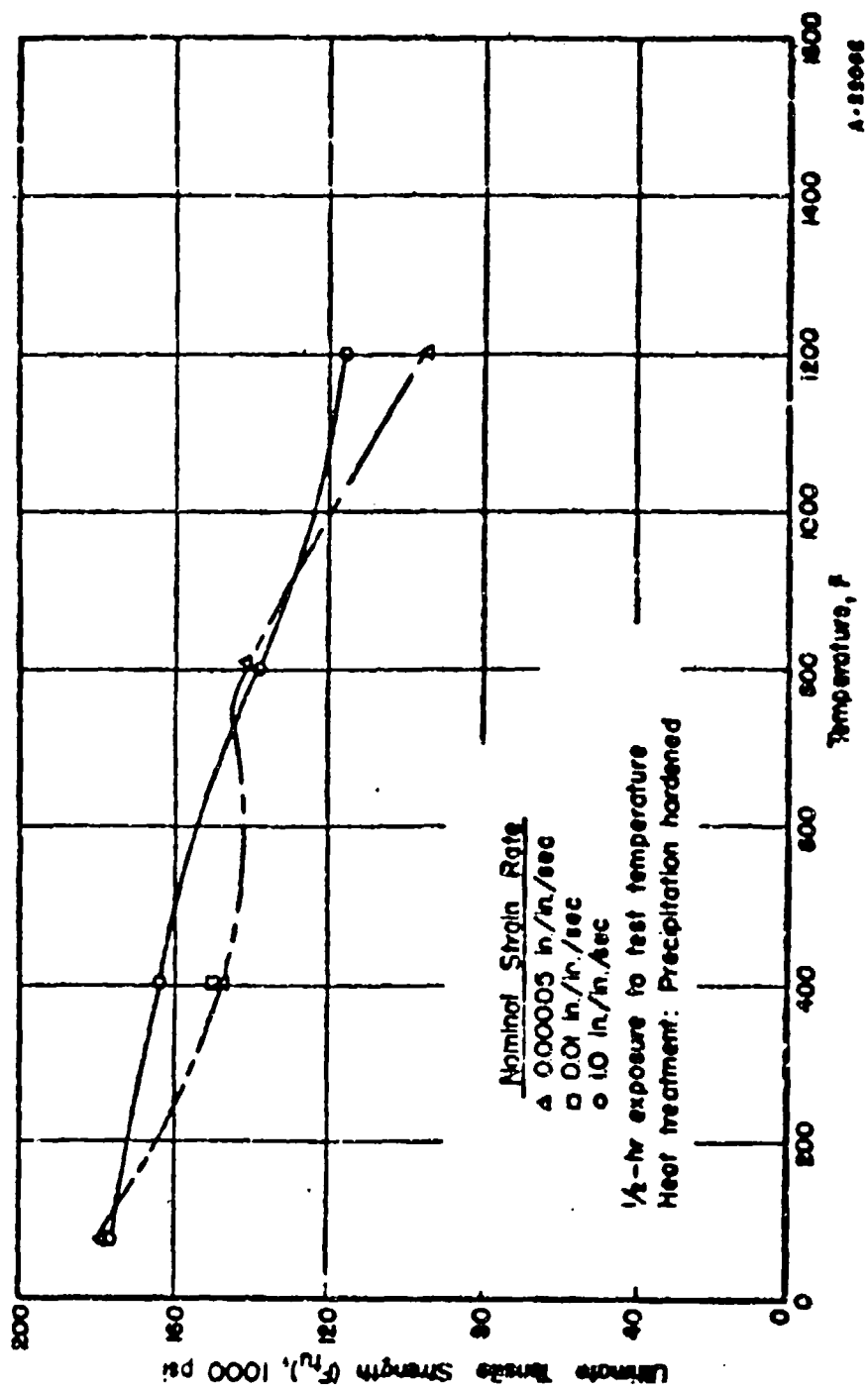
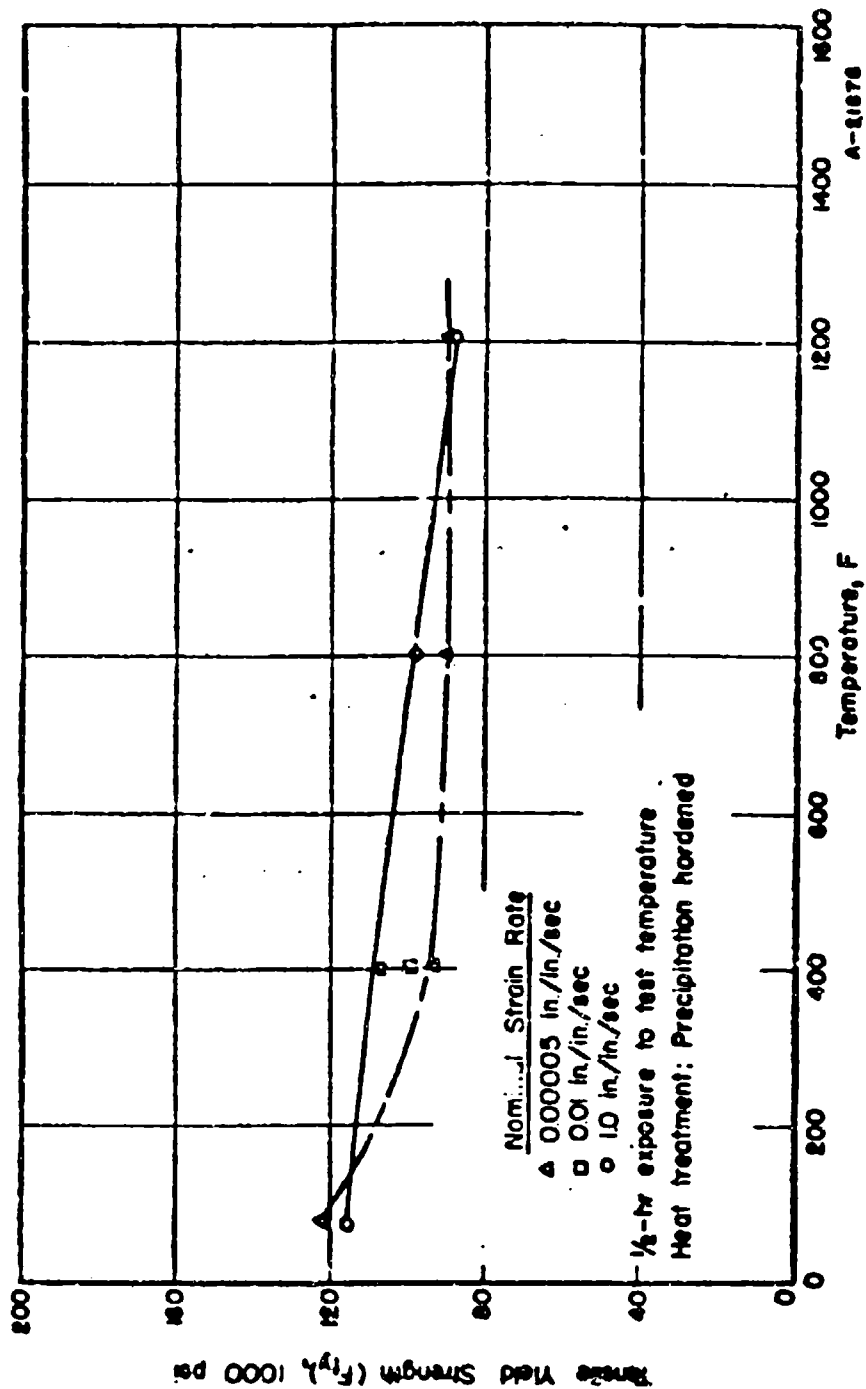


FIGURE 212. EFFECT OF STRAIN RATE ON THE TENSILE STRENGTH (F_u) OF INCONEL "X" AT ELEVATED TEMPERATURE

Ref. WADC 55-199, Part 2, p 46.



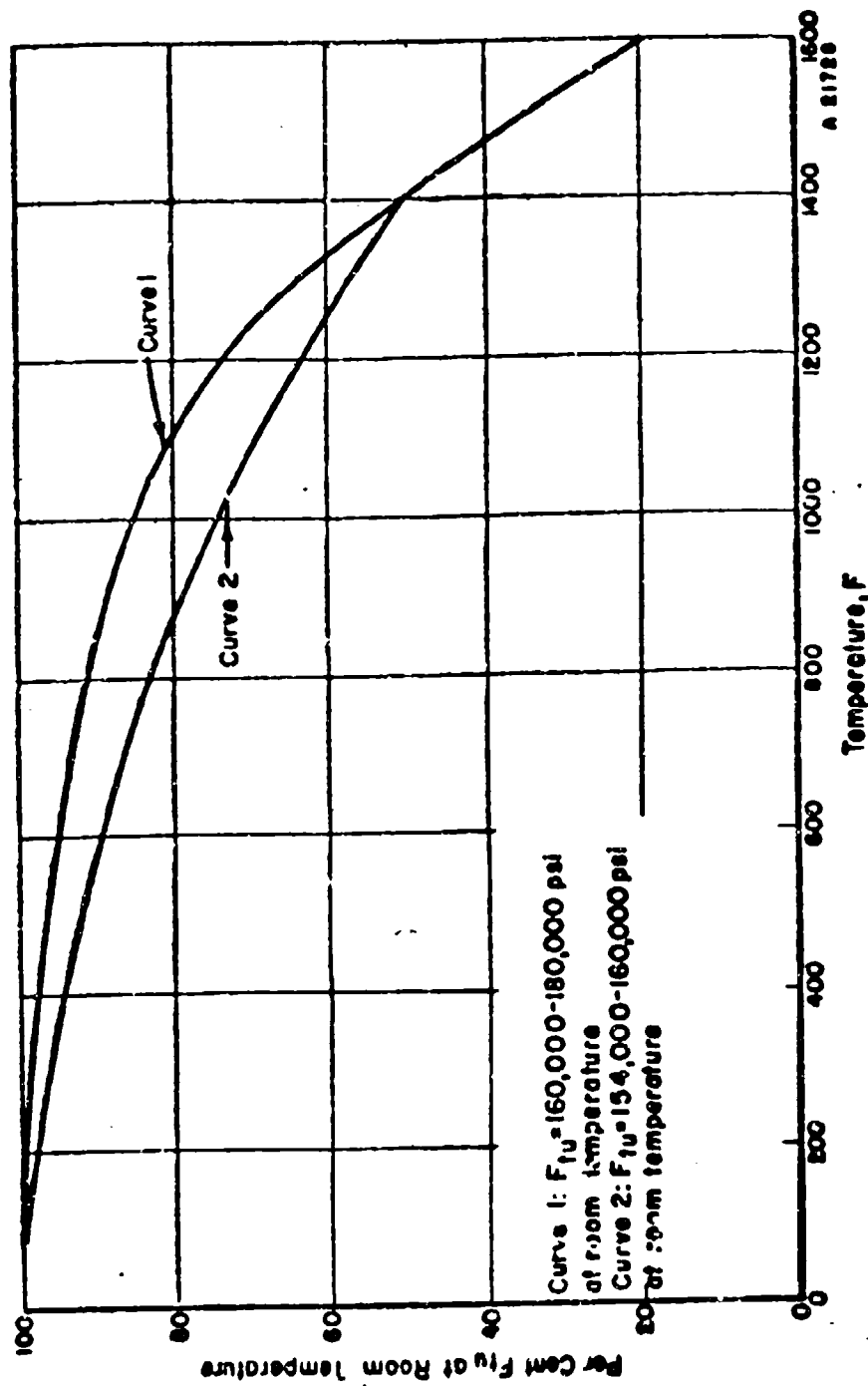


FIGURE 214. DESIGN CURVE FOR TENSILE STRENGTH (F_{tu}) OF INCONEL "X" AT ELEVATED TEMPERATURE

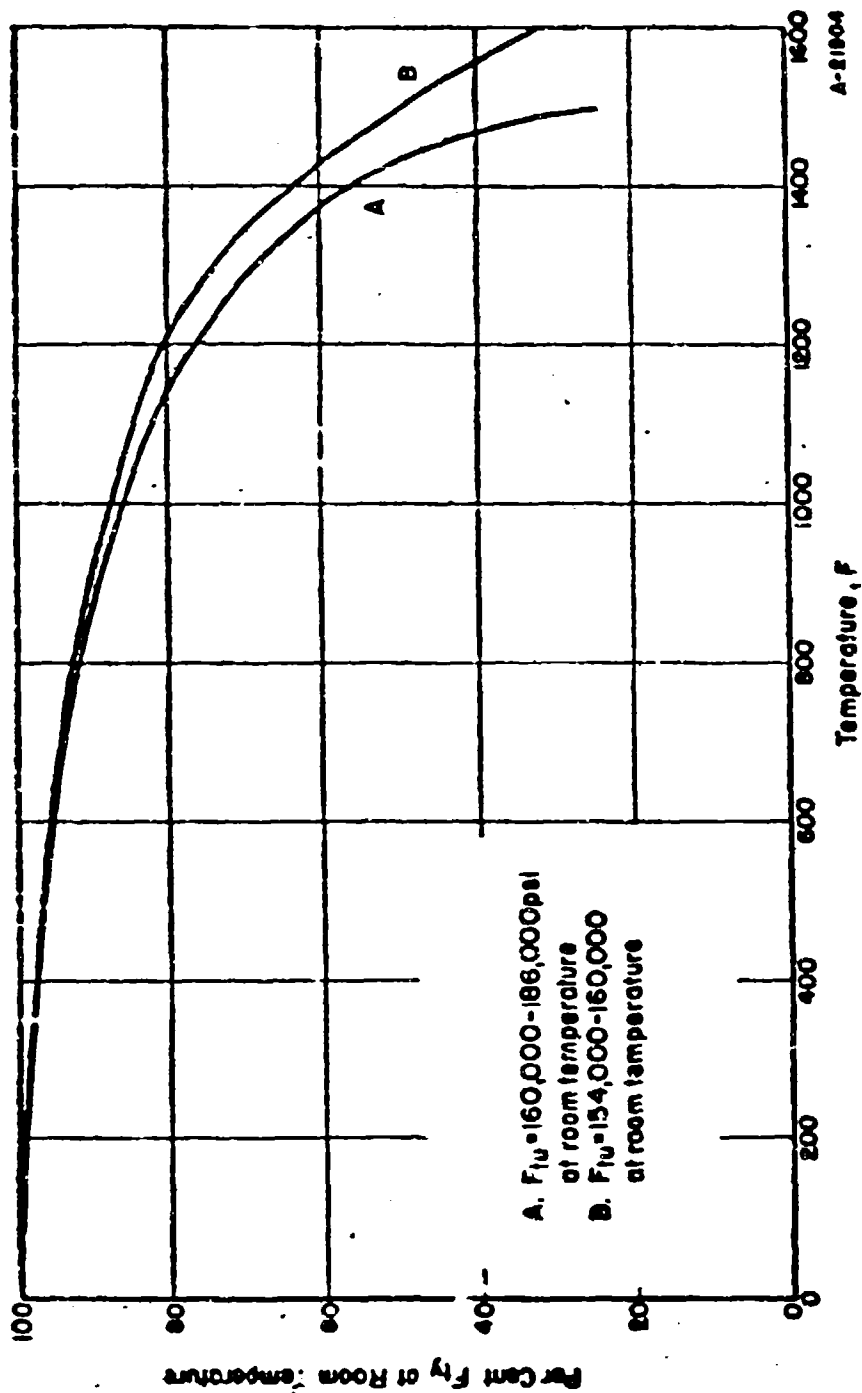


FIGURE 219. DESIGN CURVE FOR TENSILE YIELD STRENGTH (F_{ty}) OF INCONEL "X" AT ELEVATED TEMPERATURE

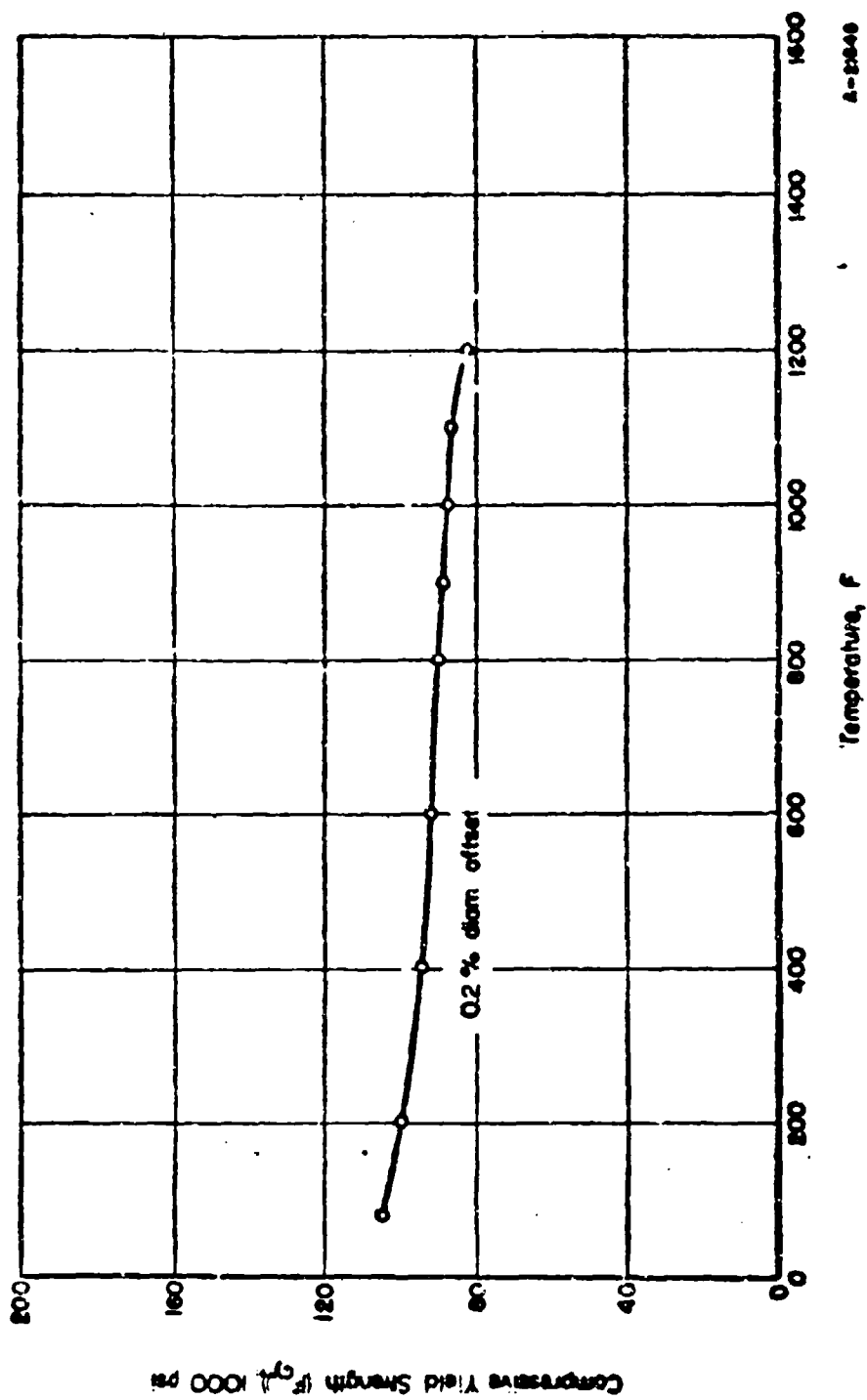


FIGURE 216. COMPRESSIVE YIELD STRENGTH (F_{cy}) OF INCONEL "X" AT ELEVATED TEMPERATURE

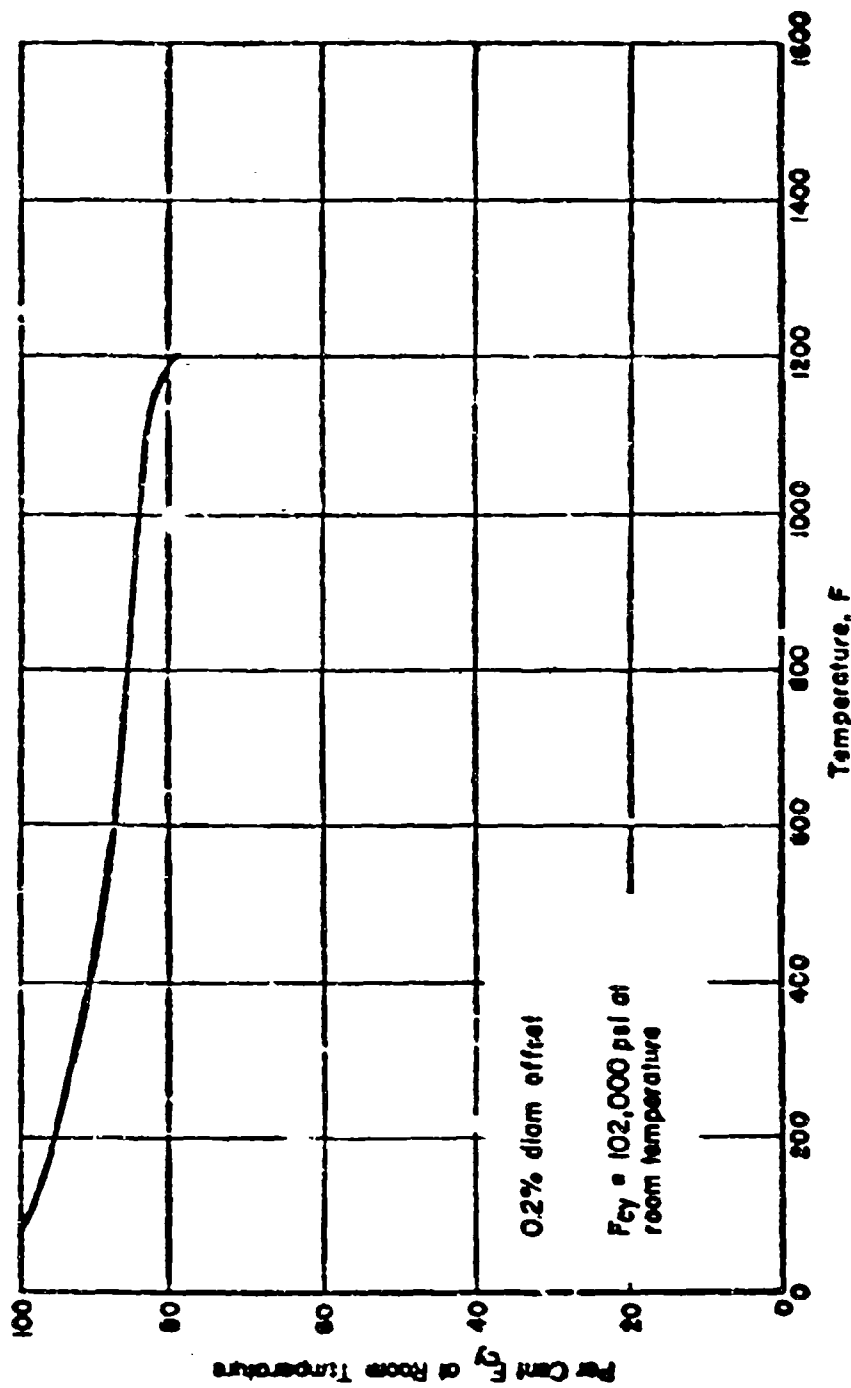


FIGURE 217. DESIGN CURVE FOR COMPRESSIVE YIELD STRENGTH (F_{cy}) OF INCONEL "X" AT ELEVATED TEMPERATURE

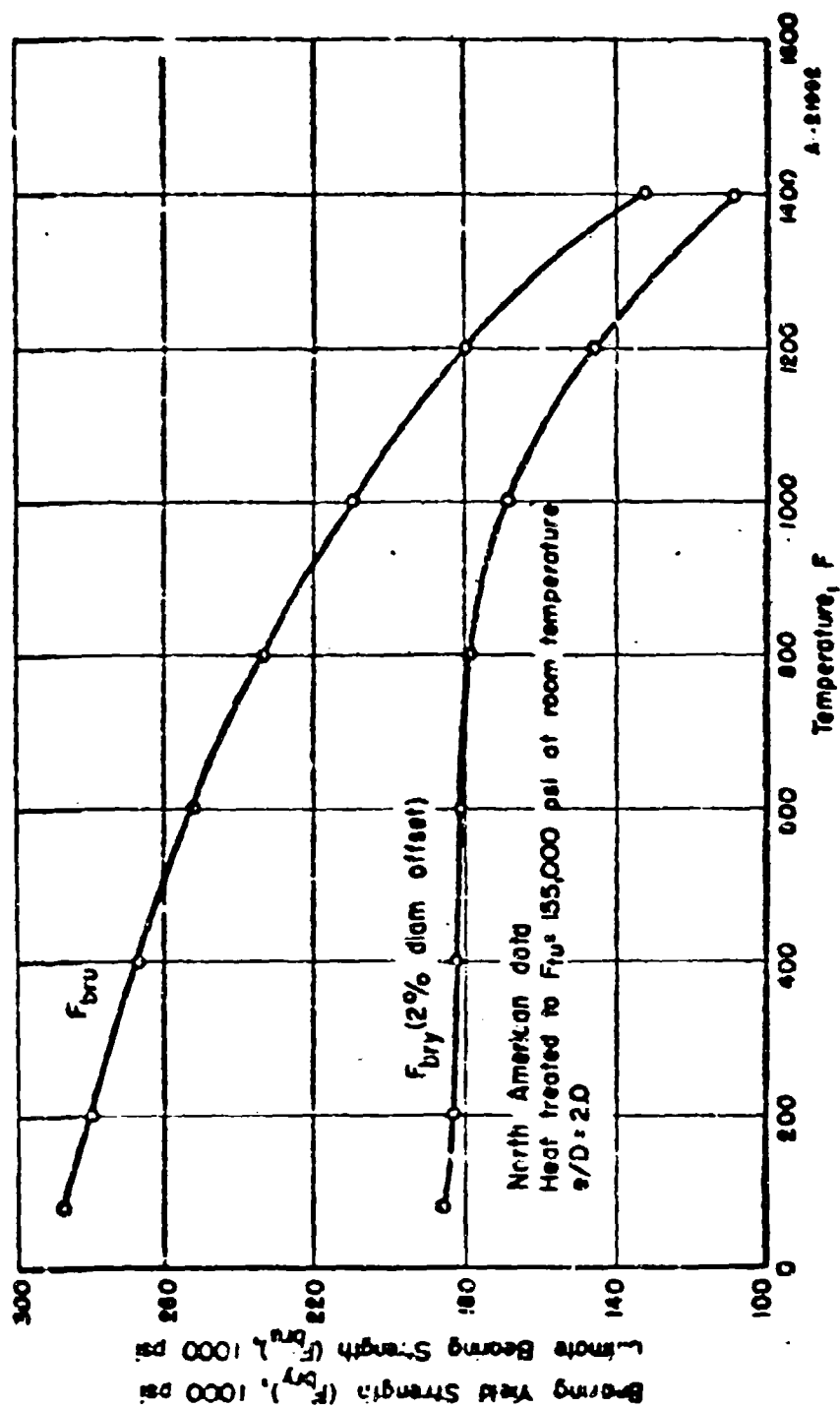


FIGURE 218. BEARING AND BEARING YIELD STRENGTH (F_{bru} AND F_{bry}) OF INCONEL "X" AT ELEVATED TEMPERATURE

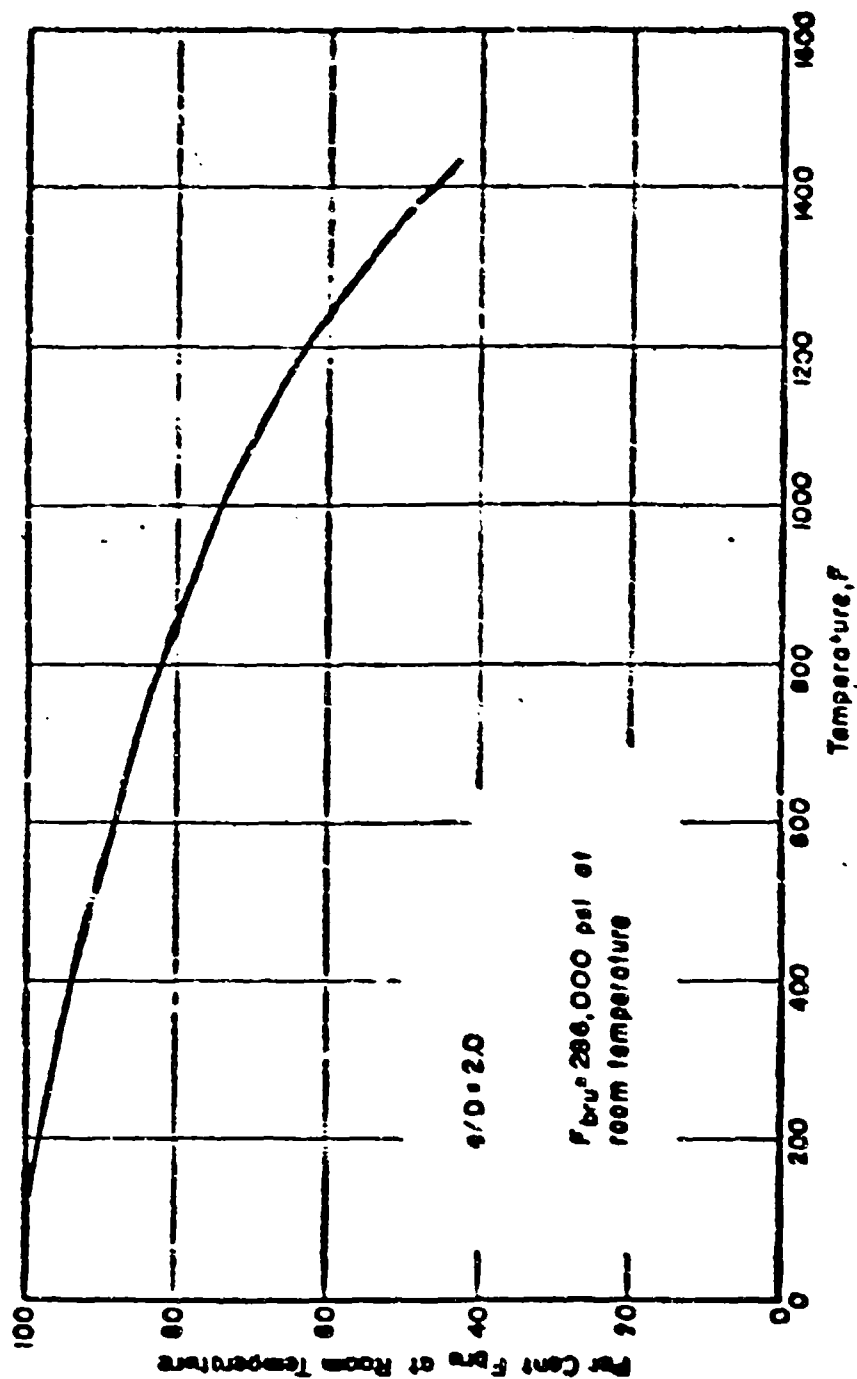


FIGURE 219. DESIGN CURVE FOR BEARING STRENGTH (F_{bru}) OF INCONEL "X" AT ELEVATED TEMPERATURE

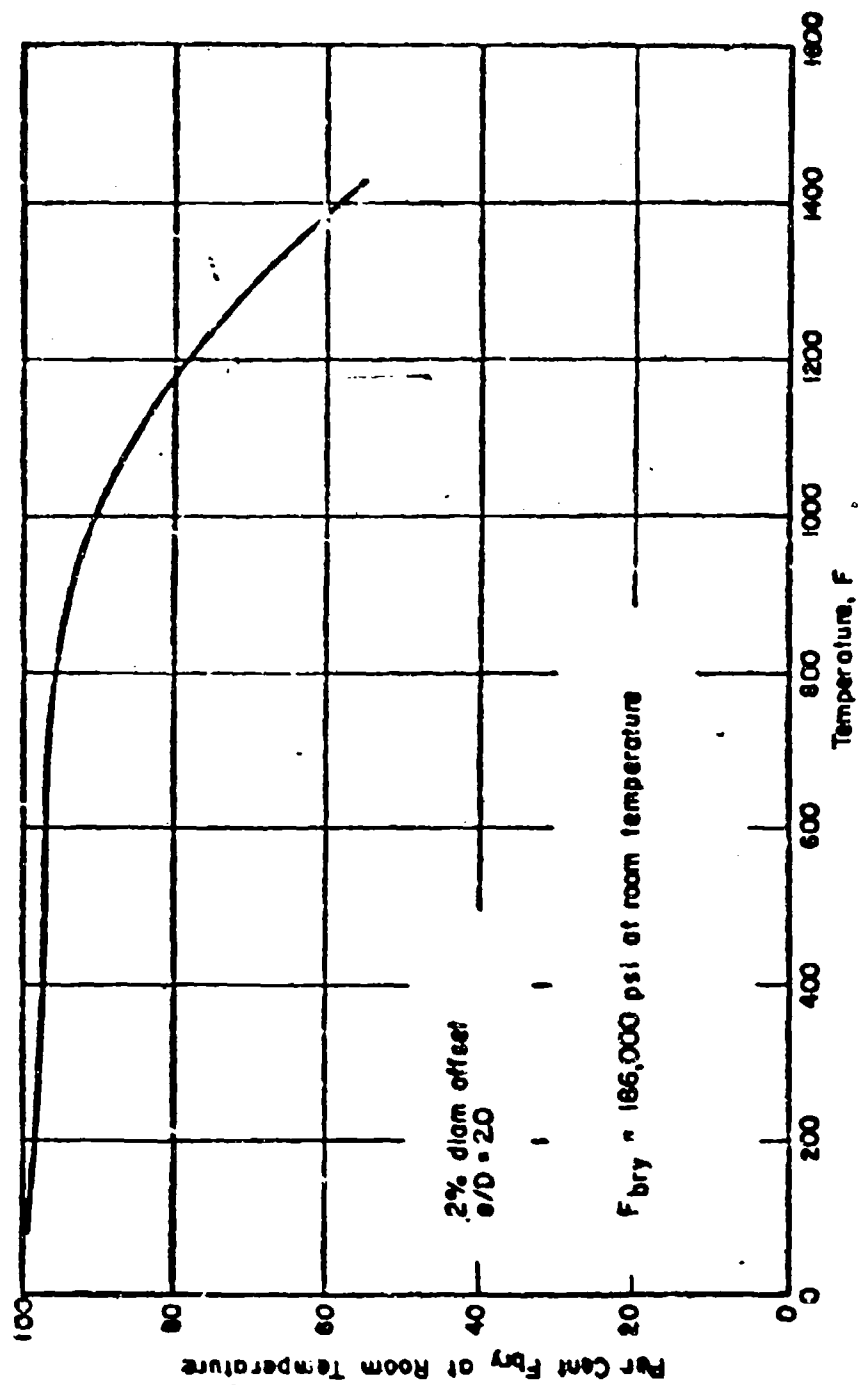


FIGURE 220. DESIGN CURVE FOR BEARING YIELD STRENGTH (F_{bry}) OF INCONEL "X" AT ELEVATED TEMPERATURE

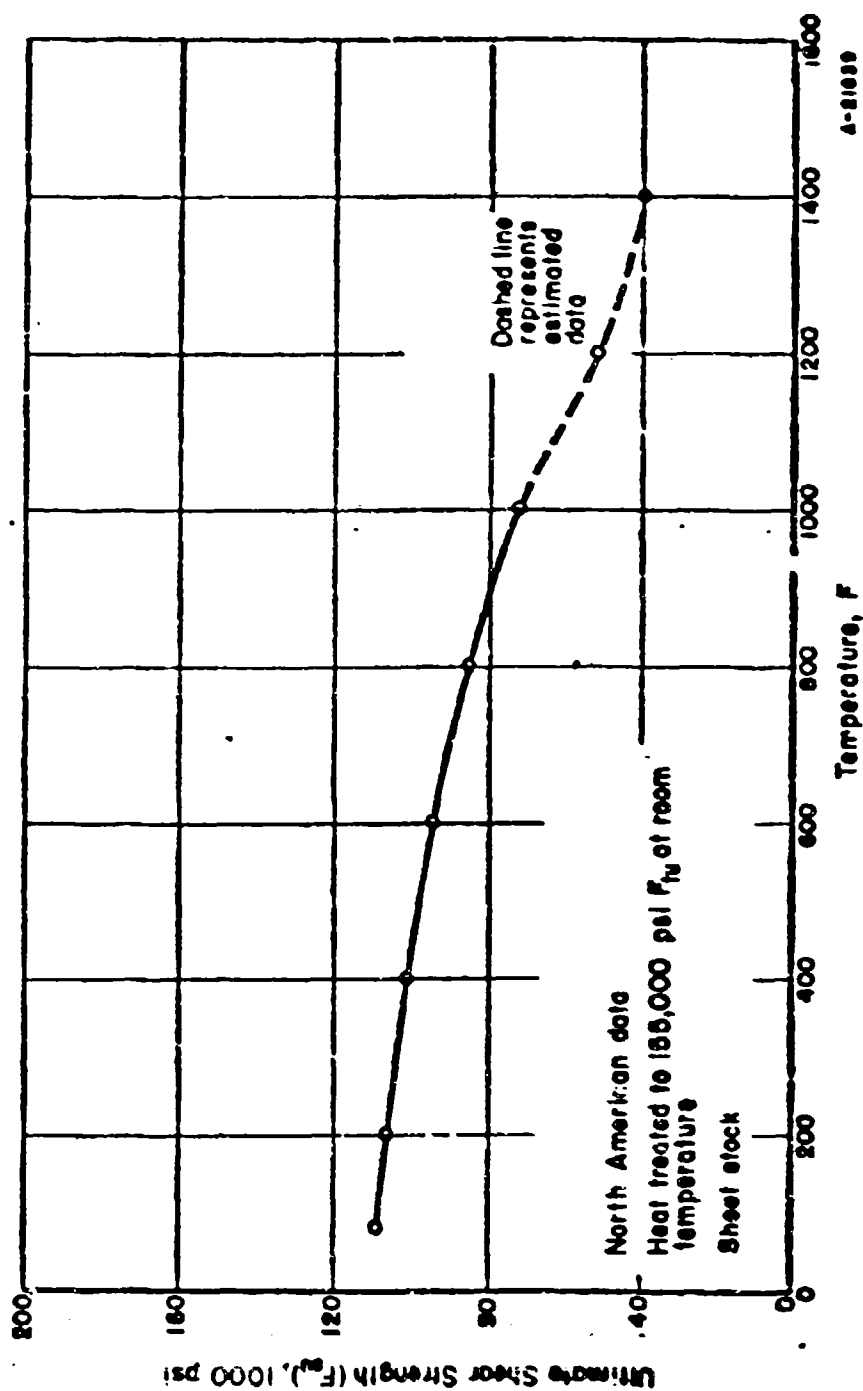


FIGURE 22.1. SHEAR STRENGTH (F_{su}) OF INCONEL "X" AT ELEVATED TEMPERATURE

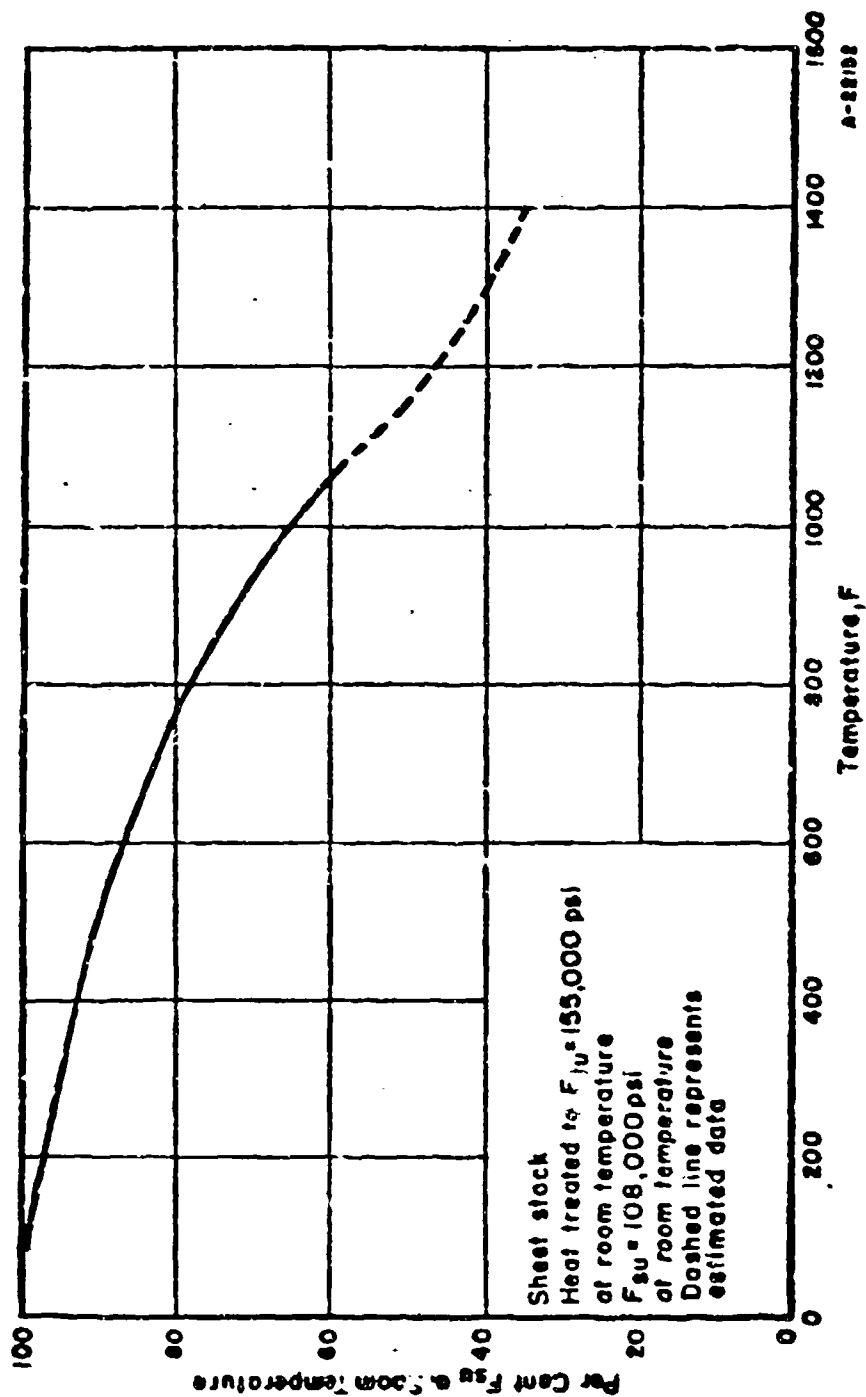
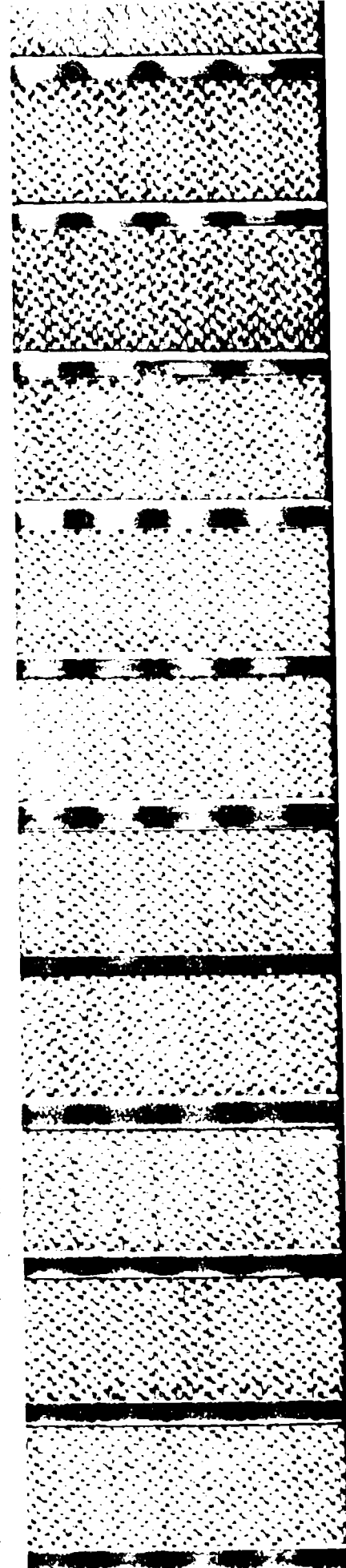
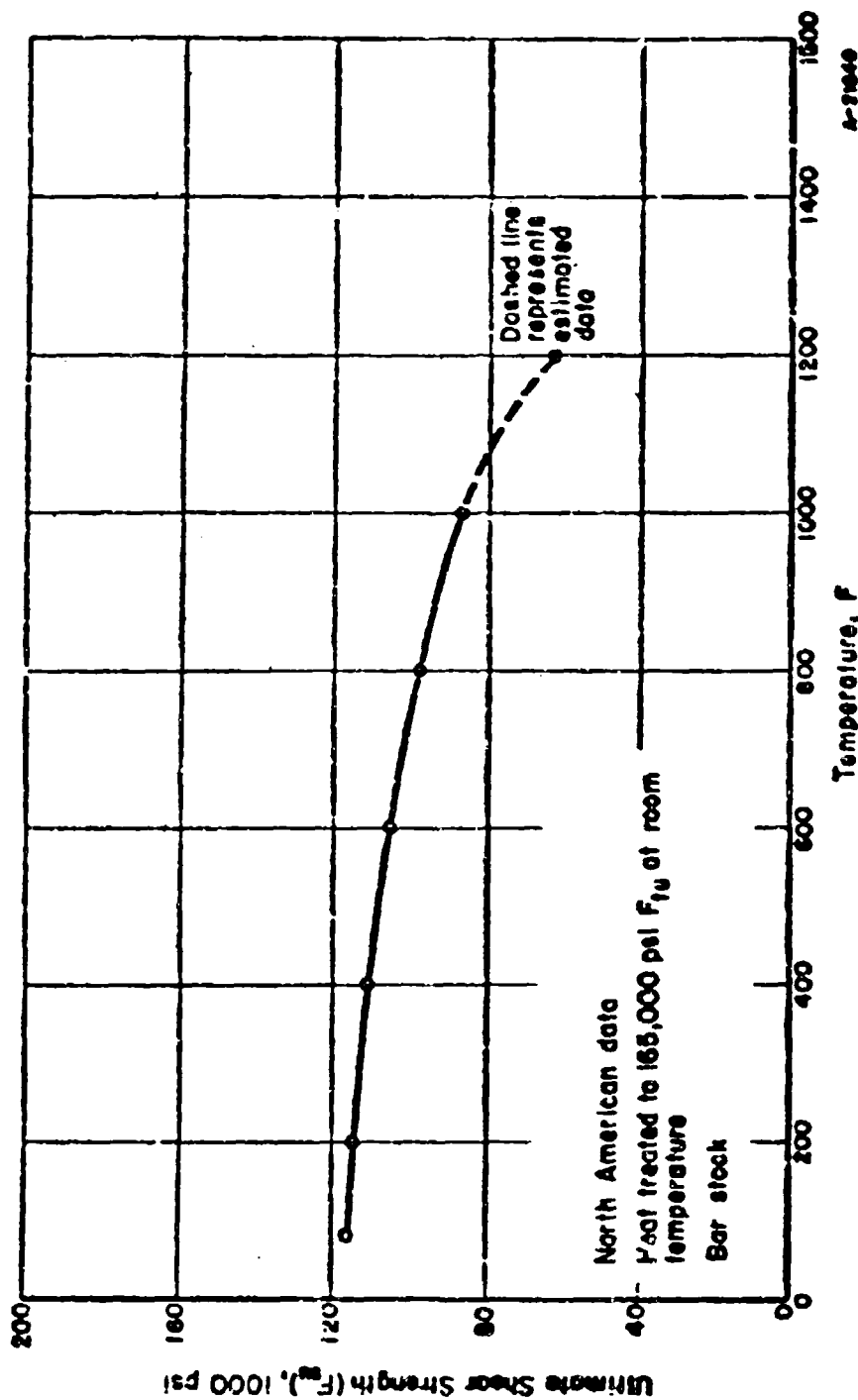


FIGURE 222. DESIGN CURVE FOR SHEAR STRENGTH (F_{su}) OF INCONEL "X"
AT ELEVATED TEMPERATURE



FIGURE 223. SHEAR STRENGTH (F_{su}) OF INCONEL "X" AT ELEVATED TEMPERATURE

Ref. 377.

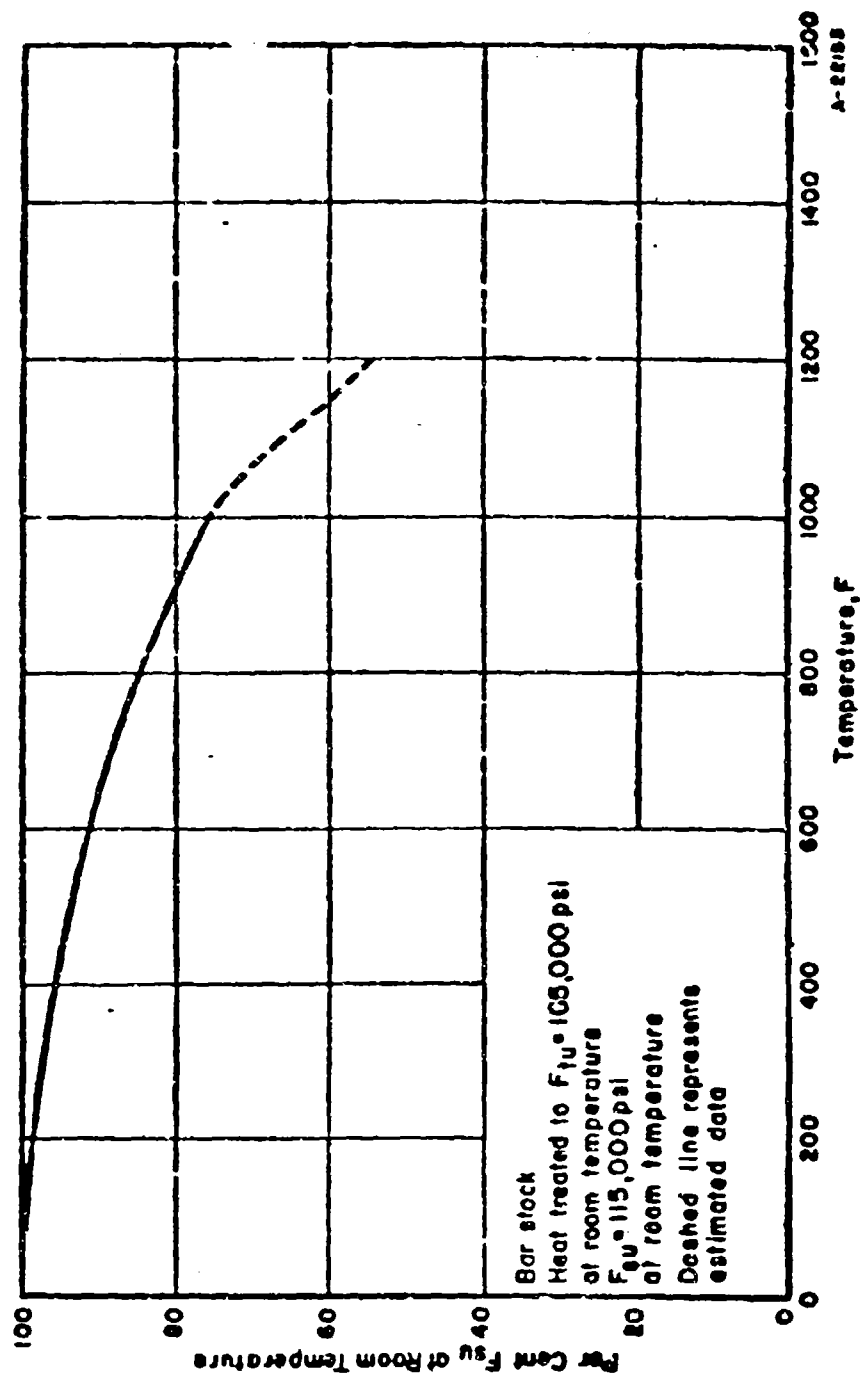


FIGURE 224. DESIGN CURVE FOR SHEAR STRENGTH (F_{su}) OF INCONEL "X" AT ELEVATED TEMPERATURE

A-22185

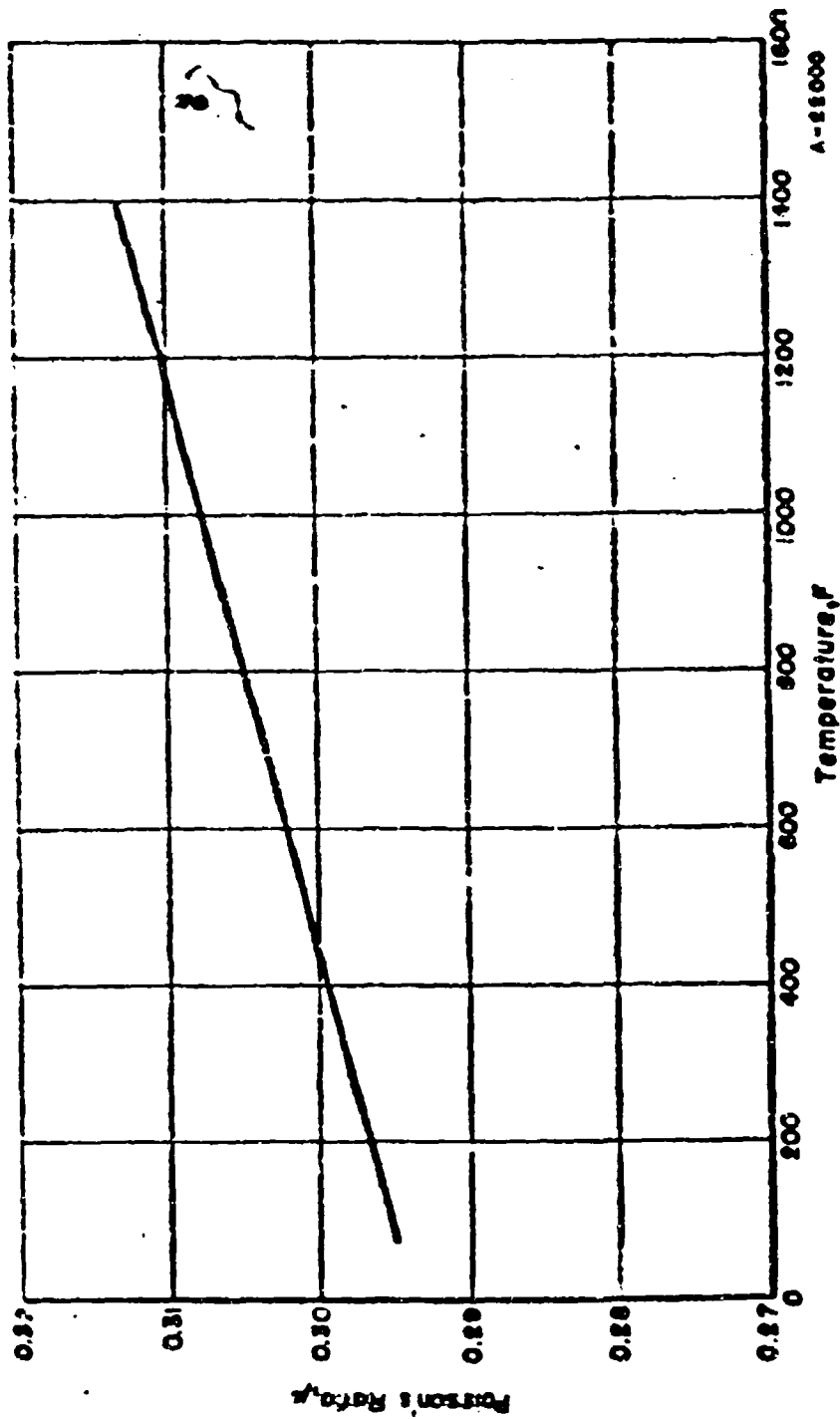


FIGURE 246. EFFECT OF ELEVATED TEMPERATURE ON POISSON'S RATIO (μ) FOR INCONEL "X"

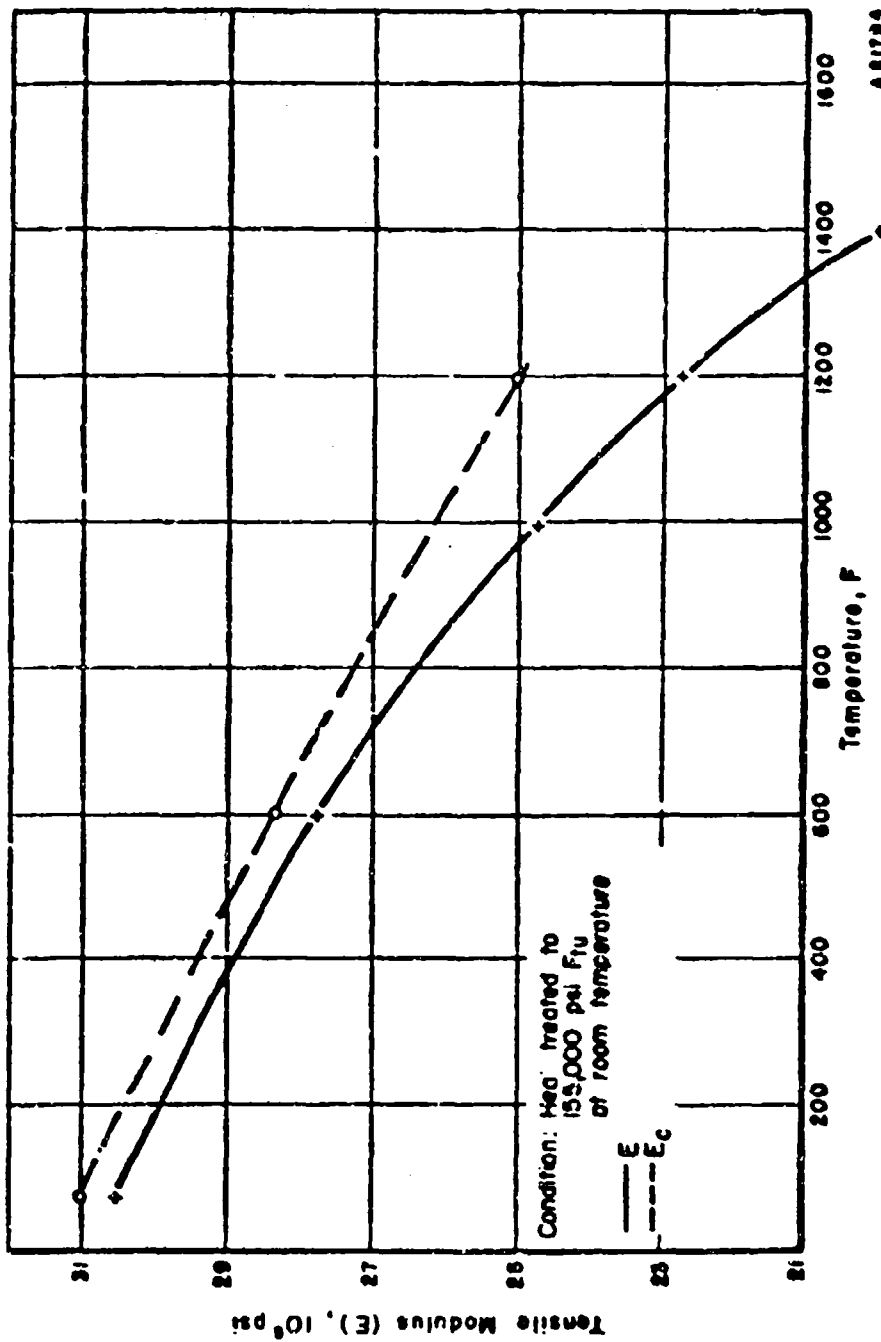


FIGURE 227. TENSILE AND COMPRESSIVE MODULI (E AND E_c) OF INCONEL "X" AT ELEVATED TEMPERATURE
Ref. 207.

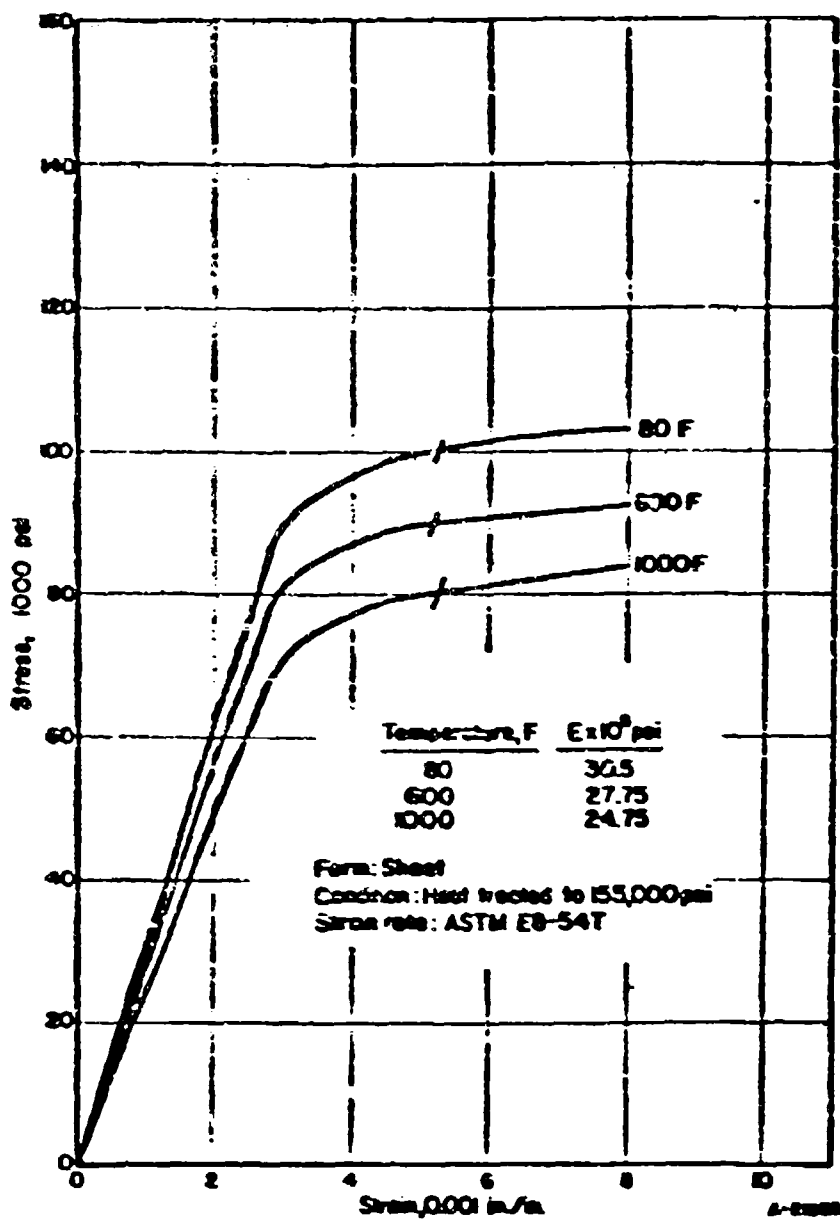


FIGURE 23A. TENSILE STRESS-STRAIN CURVES FOR INCONEL
"X" AT ROOM AND ELEVATED TEMPERATURE

ML-N-7786A (ASG)

Rev. 207, p 9-2-7-2

WASCO RE 53-030 PL 5

251

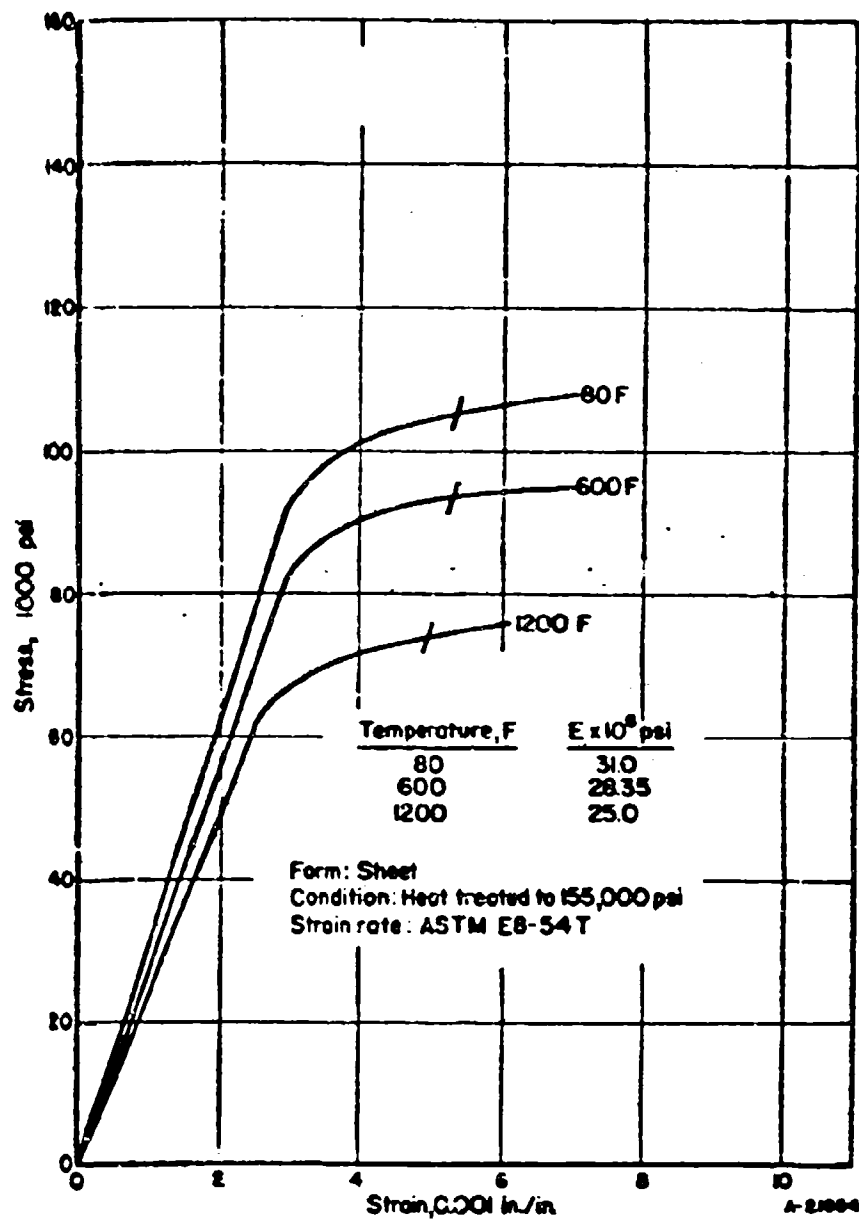


FIGURE 229. COMPRESSIVE STRESS-STRAIN CURVES FOR INCONEL "X" AT ROOM AND ELEVATED TEMPERATURE

MIL-N-7786A (ASG)
Ref. 207, p 9-2-7-2.
WADC TR 55-150 Pt 5 252

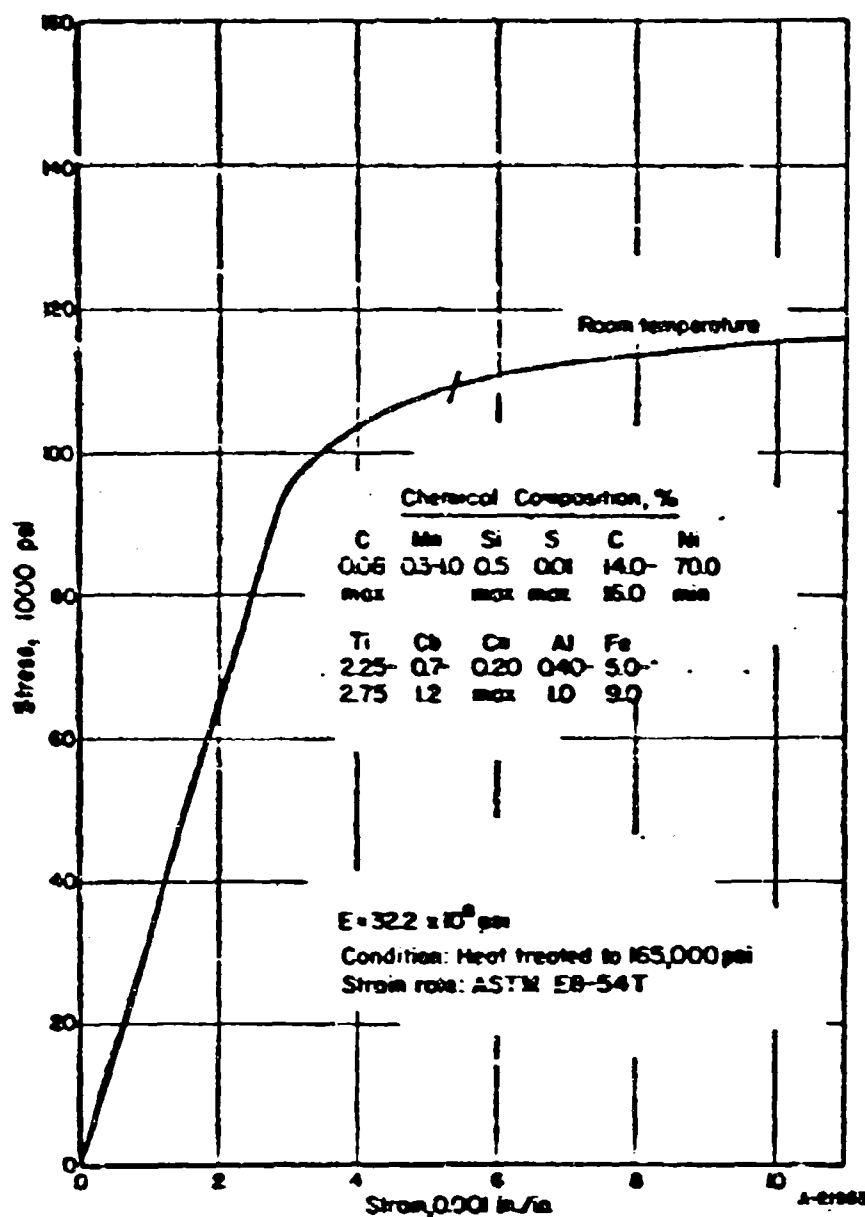


FIGURE 230. TENSILE STRESS-STRAIN CURVE FOR INCONEL "X" AT ROOM TEMPERATURE

Ref. 207, 1-9-2-7.

STAINLESS "W" ALLOY

Stainless "W" is a ferritic-type stainless steel. Because of additions of titanium and aluminum, the steel responds to a precipitation-hardening heat treatment for increased strength and hardness. The nominal composition of Stainless "W" is shown in Table 19.

TABLE 19. NOMINAL CHEMICAL
COMPOSITION OF
STAINLESS "W"
ALLOY

Element	Weight Per Cent
Carbon	0.07
Manganese	0.50
Silicon	0.50
Nickel	7.00
Chromium	17.00
Titanium	0.70
Aluminum	0.20
Iron	Balance

Heat-treating procedures are summarized as follows: (1) to solution anneal, air cool from temperatures within the range of 1200 to 2000 F (usually 1850 to 1950 F for 15 to 30 minutes); (2) to precipitation harden, heat to a temperature of 800 to 1200 F and water quench or air cool. Ultimate mechanical properties depend on holding time and temperature of precipitation hardening. Water quenching from the aging temperature produces higher strength properties.

The short-time, elevated-temperature properties of Stainless "W" are shown in the following curves:

- (1) Tensile properties, Figures 231 through 234.
- (2) Poisson's ratio, Figure 235.
- (3) Modulus of elasticity, Figure 236.
- (4) Stress-strain curves, Figures 237 through 240.

Shear, bearing, and compressive properties and stress-strain curves at elevated temperature are lacking for Stainless "W" alloy.

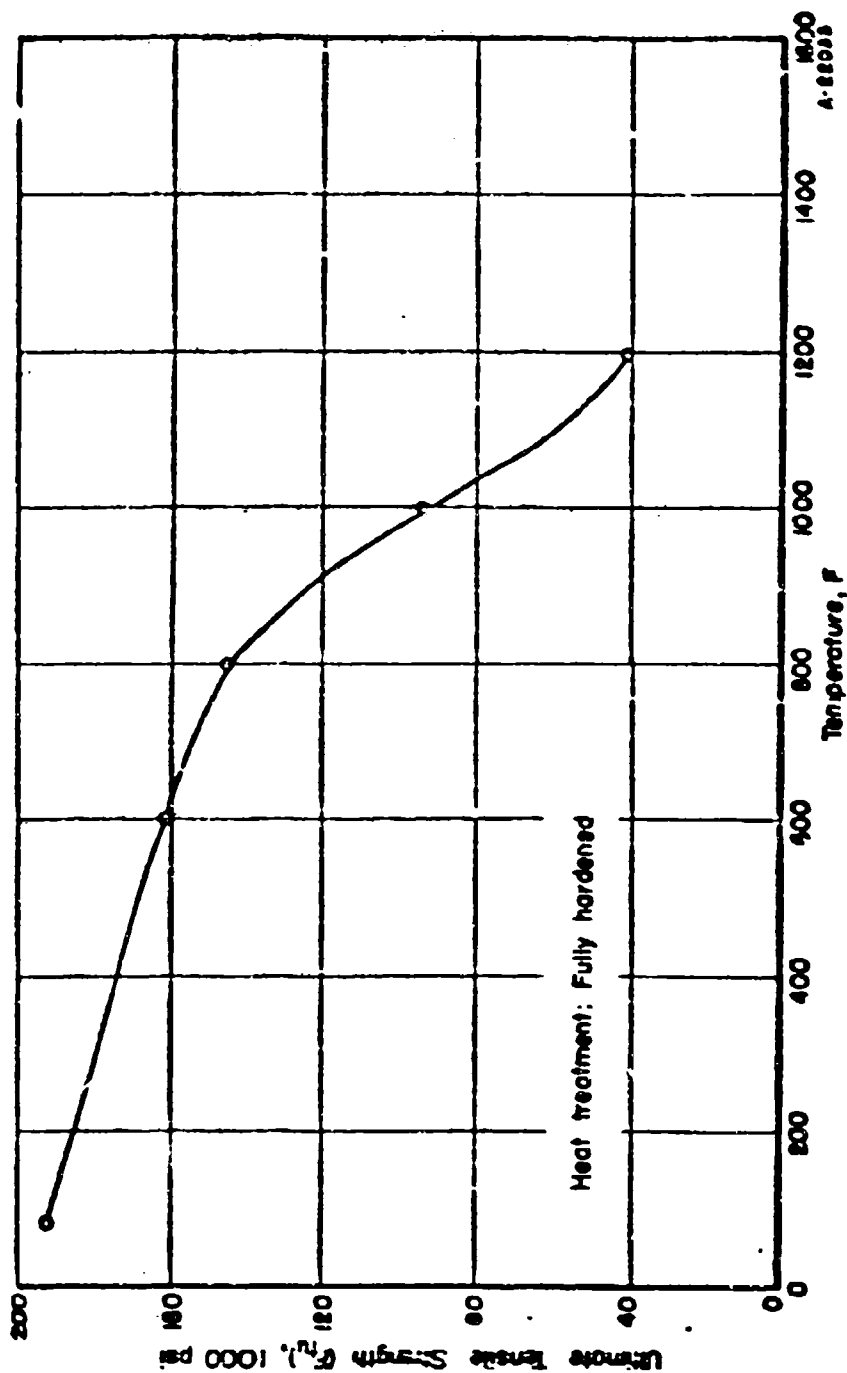


FIGURE 231. TENSILE STRENGTH (F_{tu}) OF STAINLESS "W" ALLOY AT ELEVATED TEMPERATURE

Ref. 359.

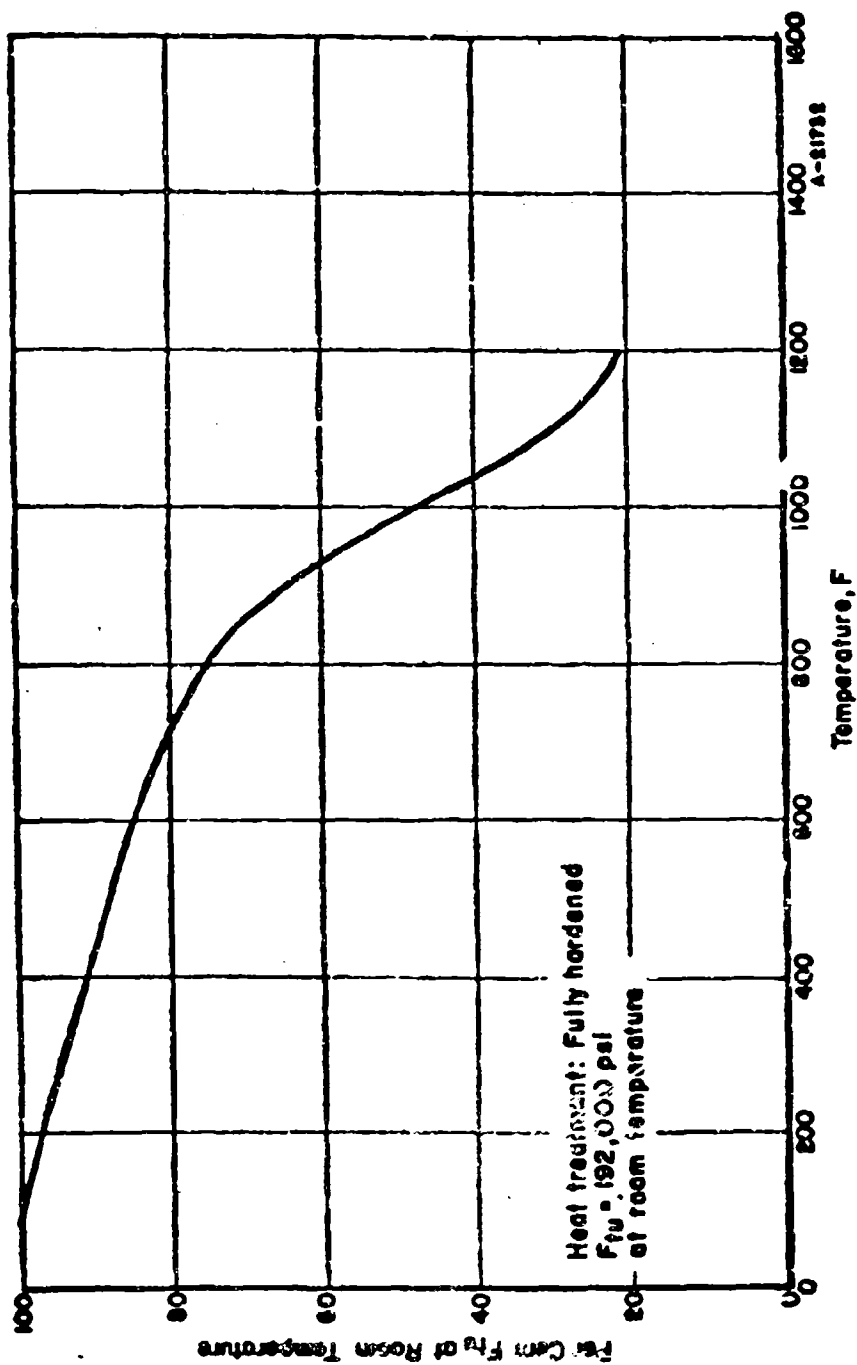


FIGURE 232. DESIGN CURVE FOR TENSILE STRENGTH (F_{tu}) OF STAINLESS "W"
 ALLOY AT ELEVATED TEMPERATURE

Ref. 358.

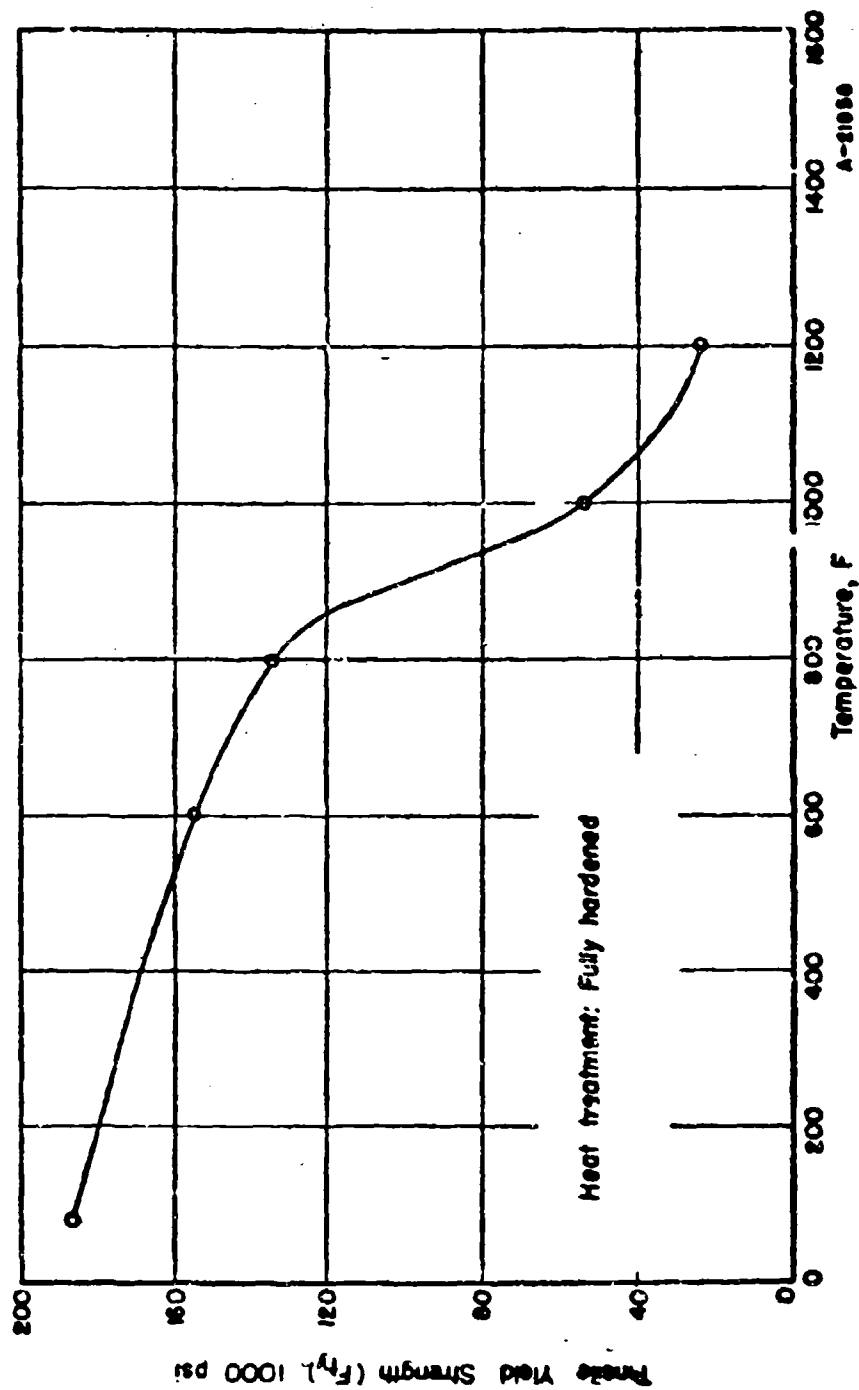


FIGURE 239. TENSILE YIELD STRENGTH (F_y) OF STAINLESS "W" ALLOY AT ELEVATED TEMPERATURE
Ref. 358.

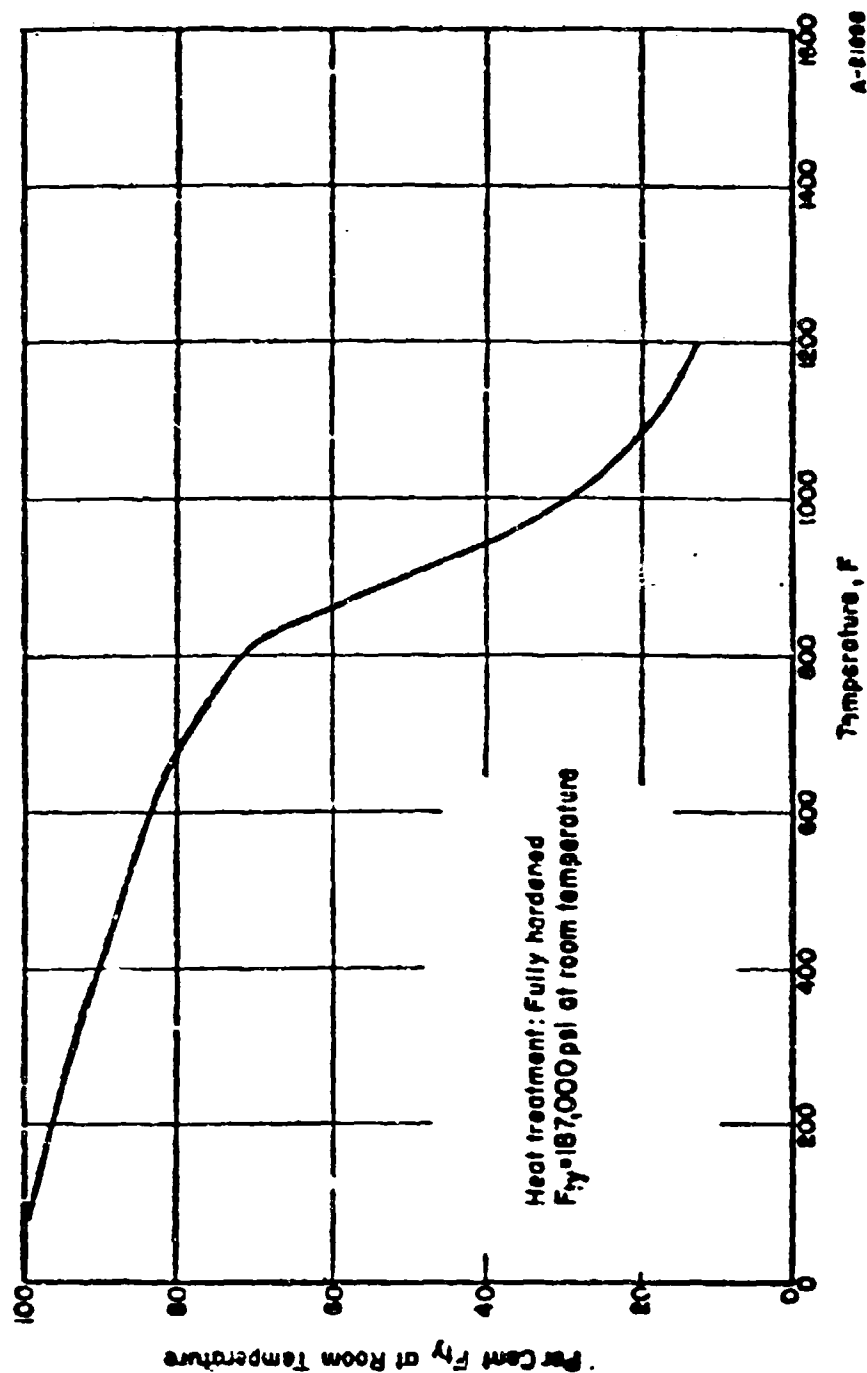


FIGURE 234. DESIGN CURVE FOR TENSILE YIELD STRENGTH (F_y) OF STAINLESS "W" ALLOY AT ELEVATED TEMPERATURE
 Ref. 358.

A-51008

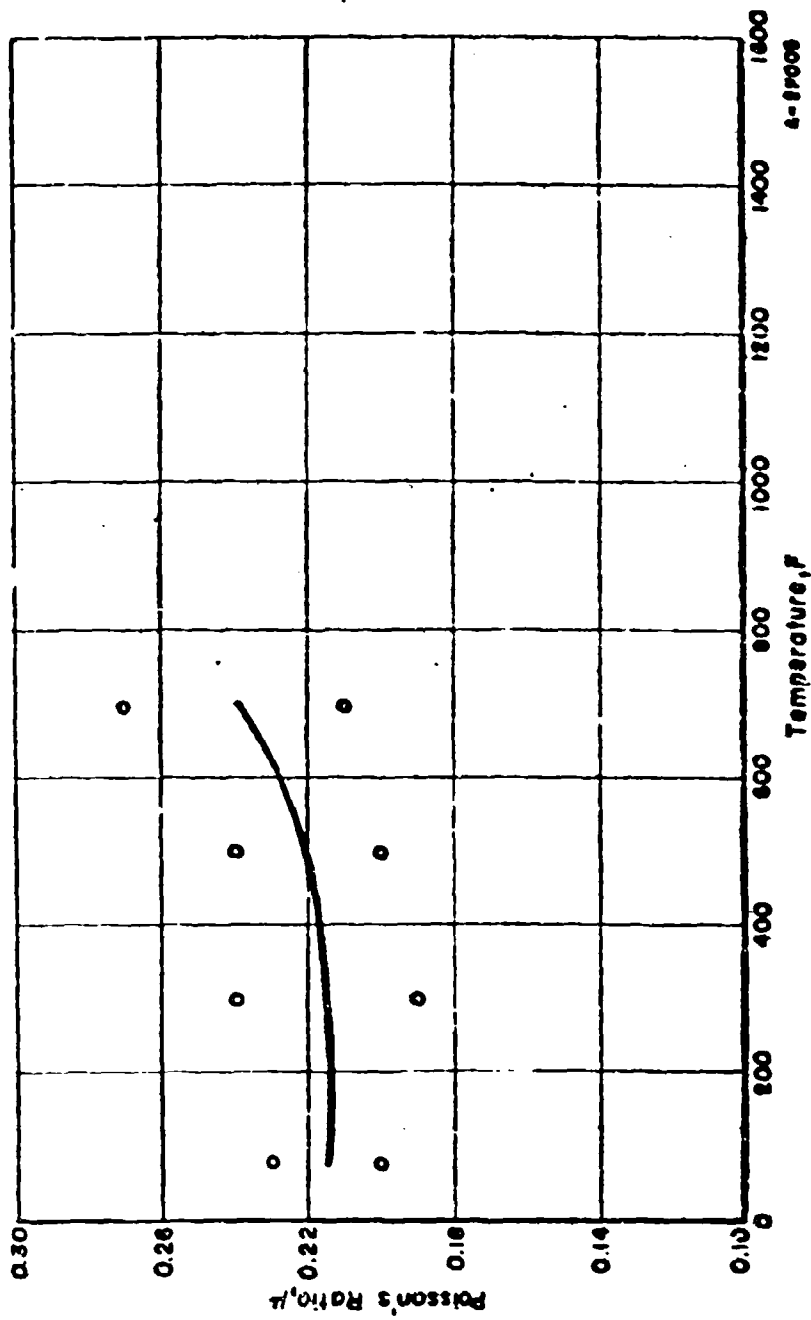


FIGURE 235. EFFECT OF ELEVATED TEMPERATURE ON POISSON'S RATIO (μ) OF STAINLESS "W" ALLOY

Ref. 358.

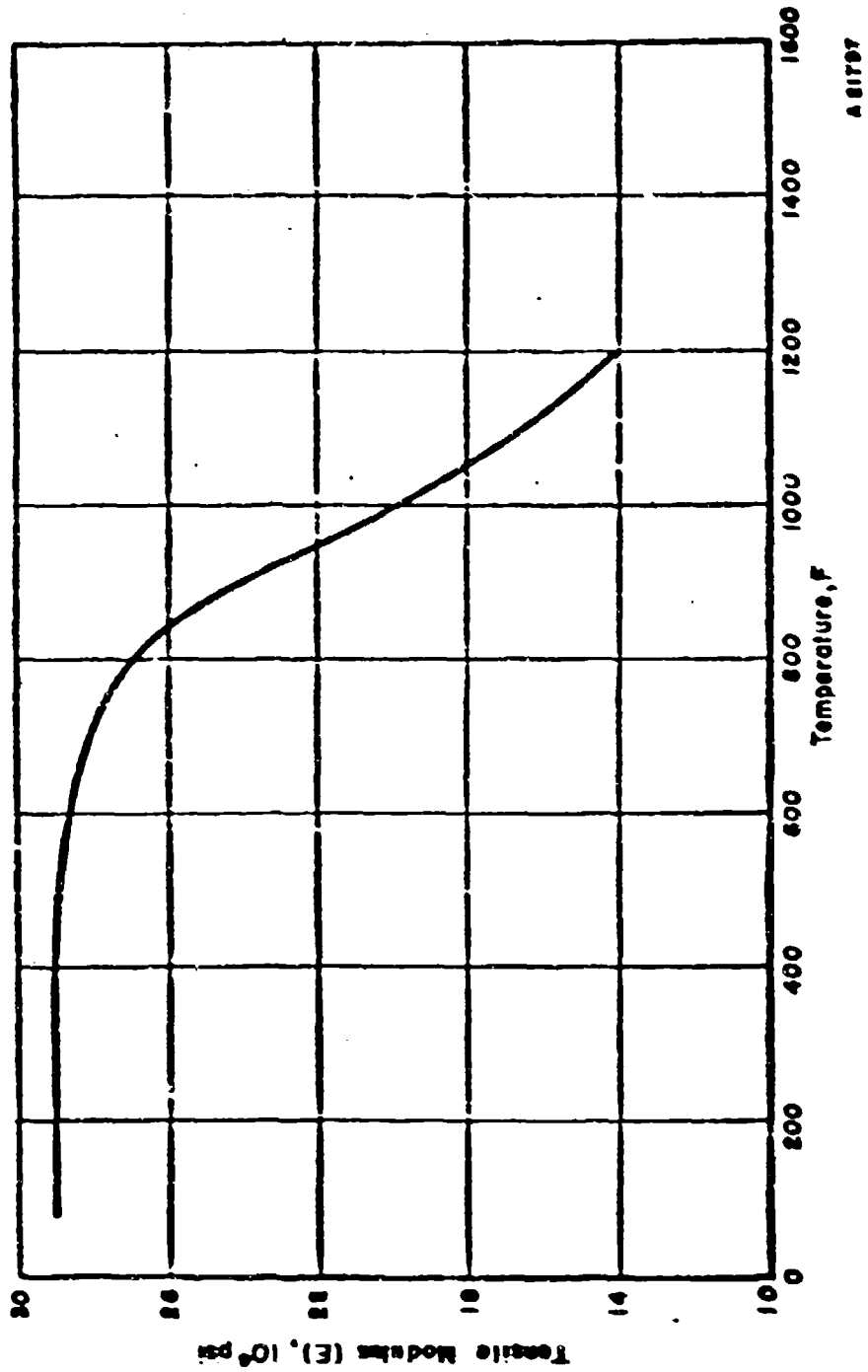


FIGURE 236. TENSILE MODULUS (E) OF STAINLESS "W" ALLOY AT ELEVATED TEMPERATURE

Ref. 358.

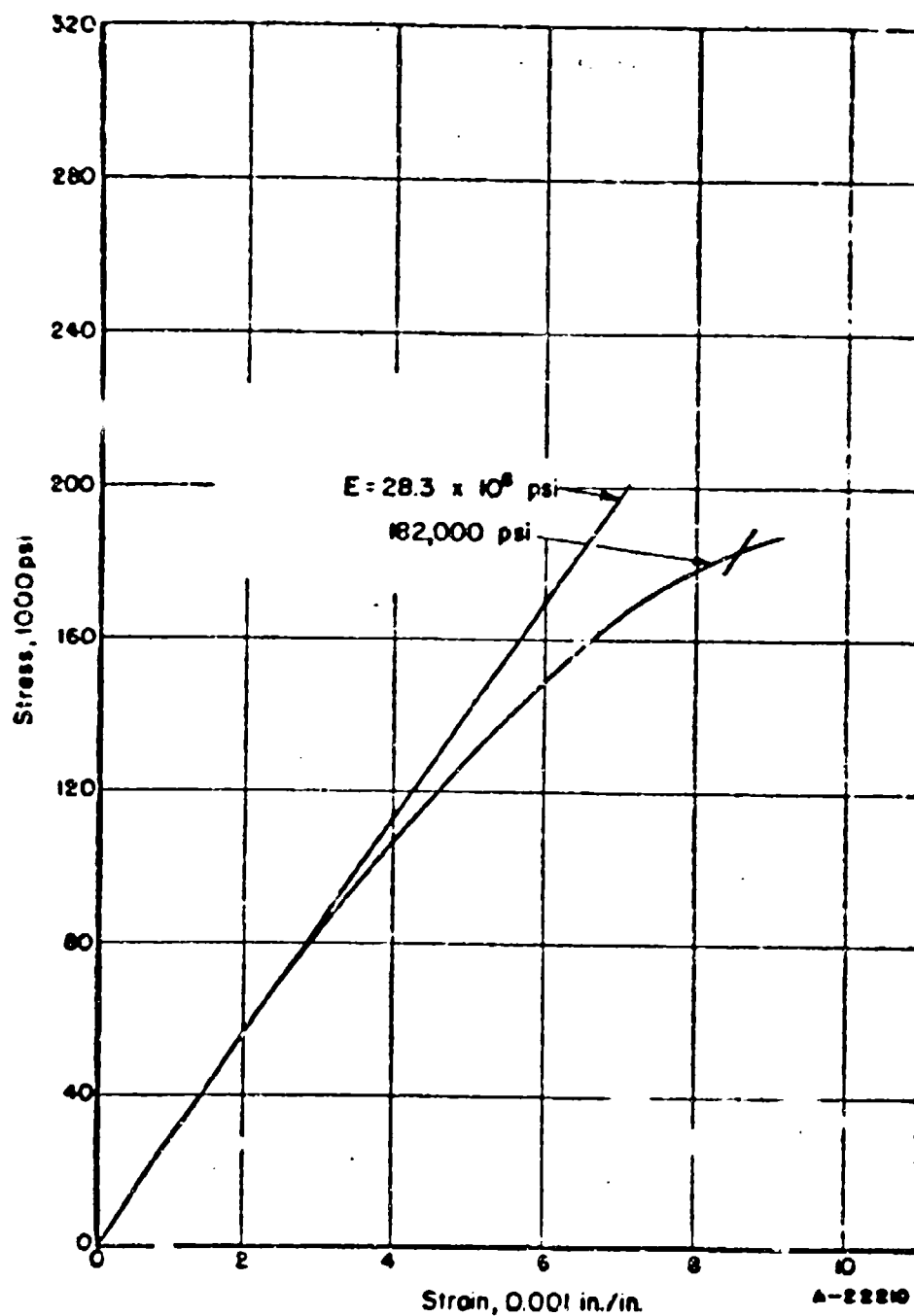


FIGURE 237. TENSILE STRESS-STRAIN CURVE FOR STAINLESS
STEEL ALLOY AT ROOM TEMPERATURE
(LONGITUDINAL PROPERTY)

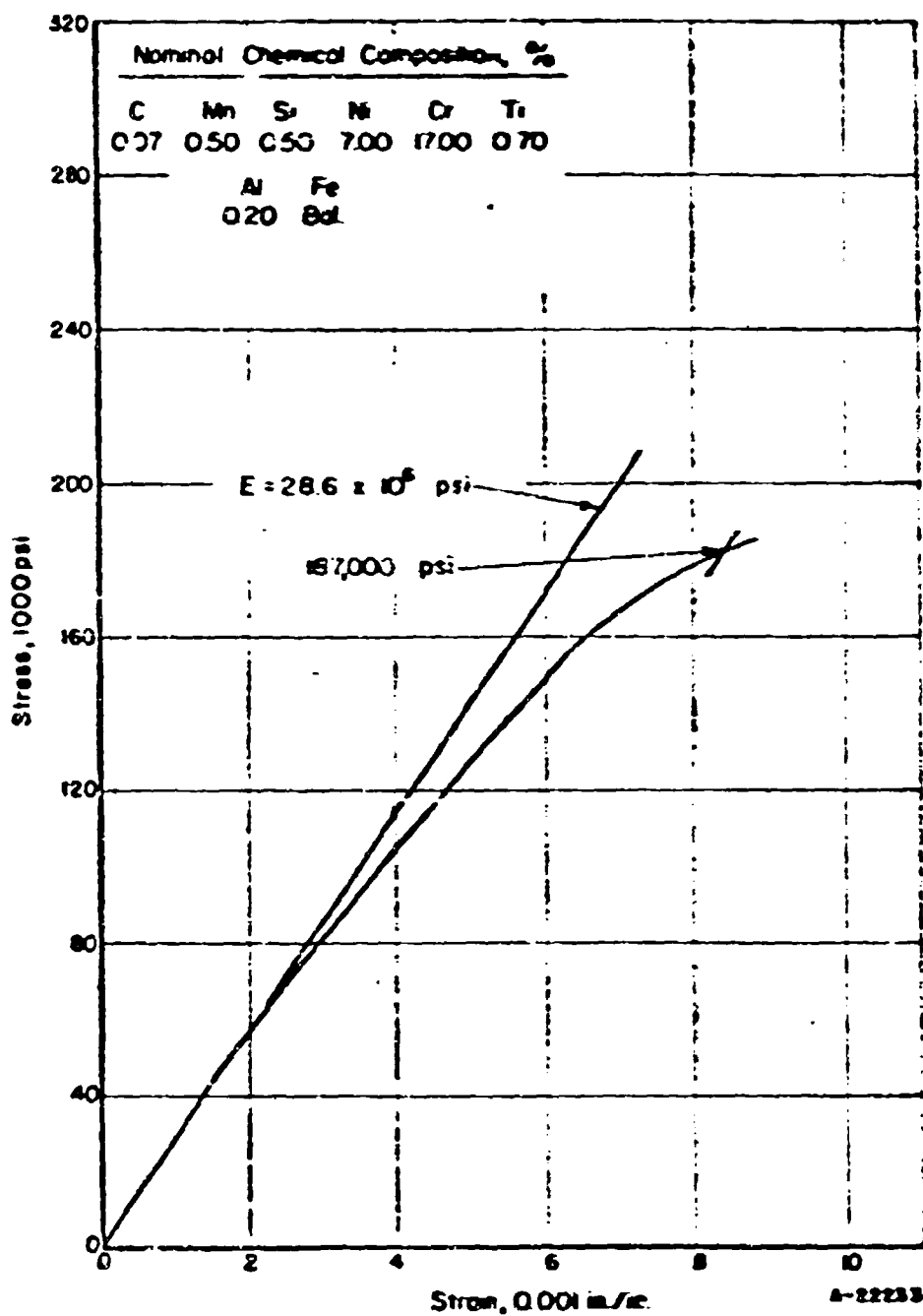


FIGURE 238. TENSILE STRESS-STRAIN CURVE FOR STAINLESS "W" ALLOY AT ROOM TEMPERATURE (TRANSVERSE PROPERTY)

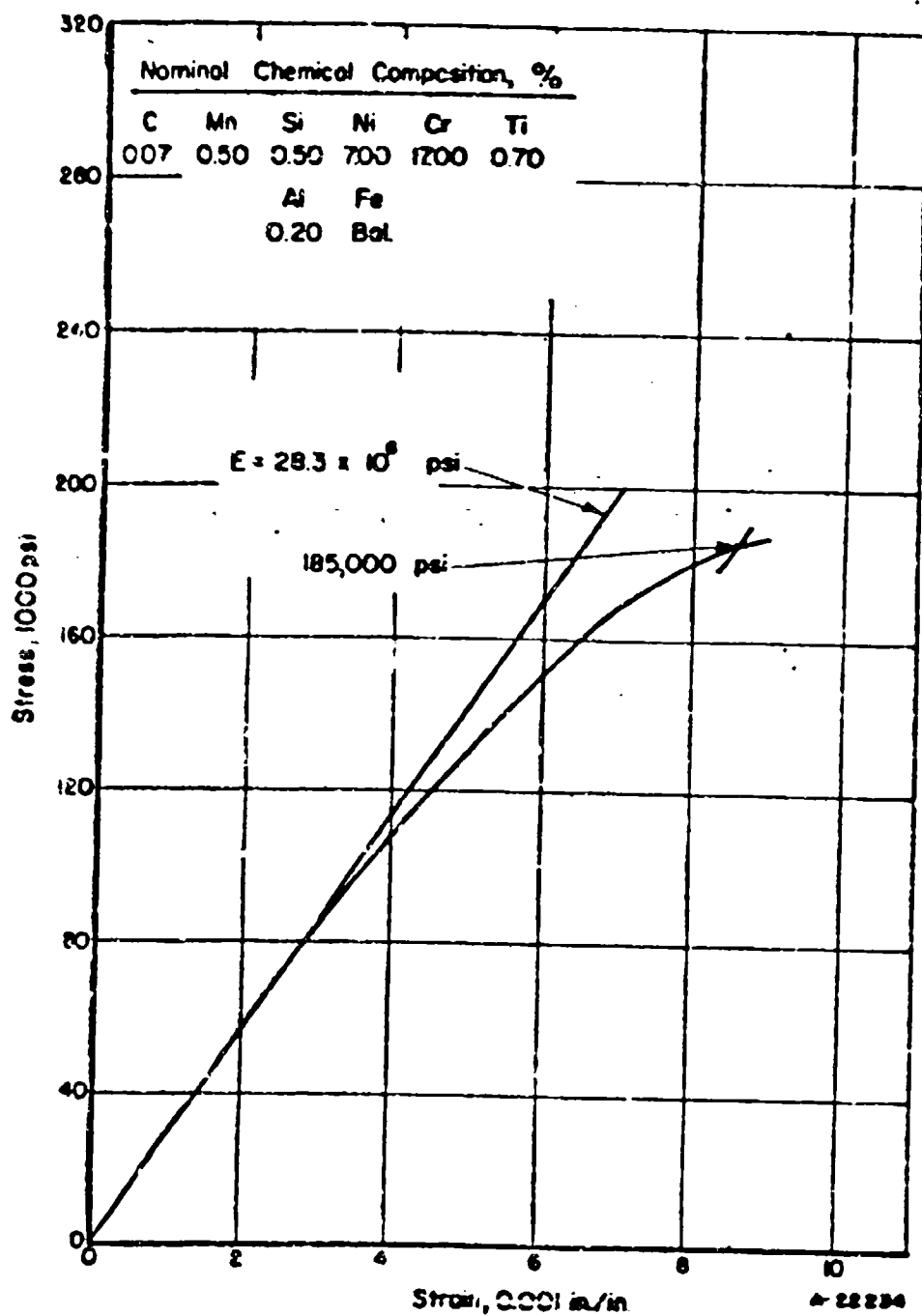


FIGURE 100. COMPRESSIVE STRESS-STRAIN CURVE FOR STAINLESS
"W" ALLOY AT ROOM TEMPERATURE
(LONGITUDINAL PROPERTY)

Re'l. 385.

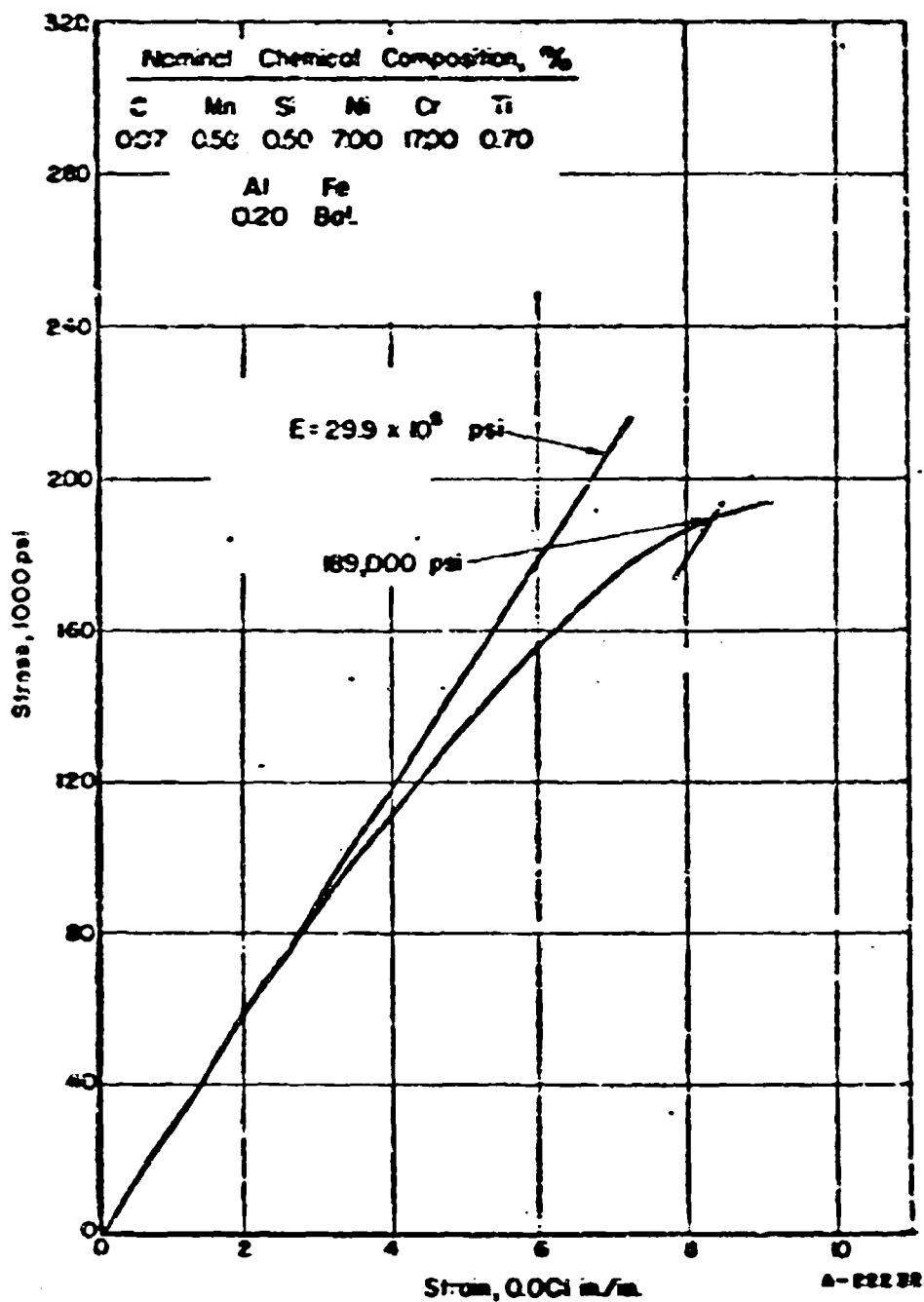


FIGURE 240. COMPRESSIVE STRESS-STRAIN CURVE FOR STAINLESS "V" ALLOY AT ROOM TEMPERATURE (TRANSVERSE PROPERTY)

APPENDIX I

MATERIAL COMPARISON CURVES

For convenience, the following curves have been plotted to show the relative strengths of the various alloys discussed in this report.

	<u>Page</u>
Figure 241. Comparison of Tensile Strengths (F_{tu}) of Stainless Steels and Super Alloys at Elevated Temperature	266
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Figure 247. Comparison of Shear Strengths (F_{su}) of Stainless Steels at Elevated Temperature	272

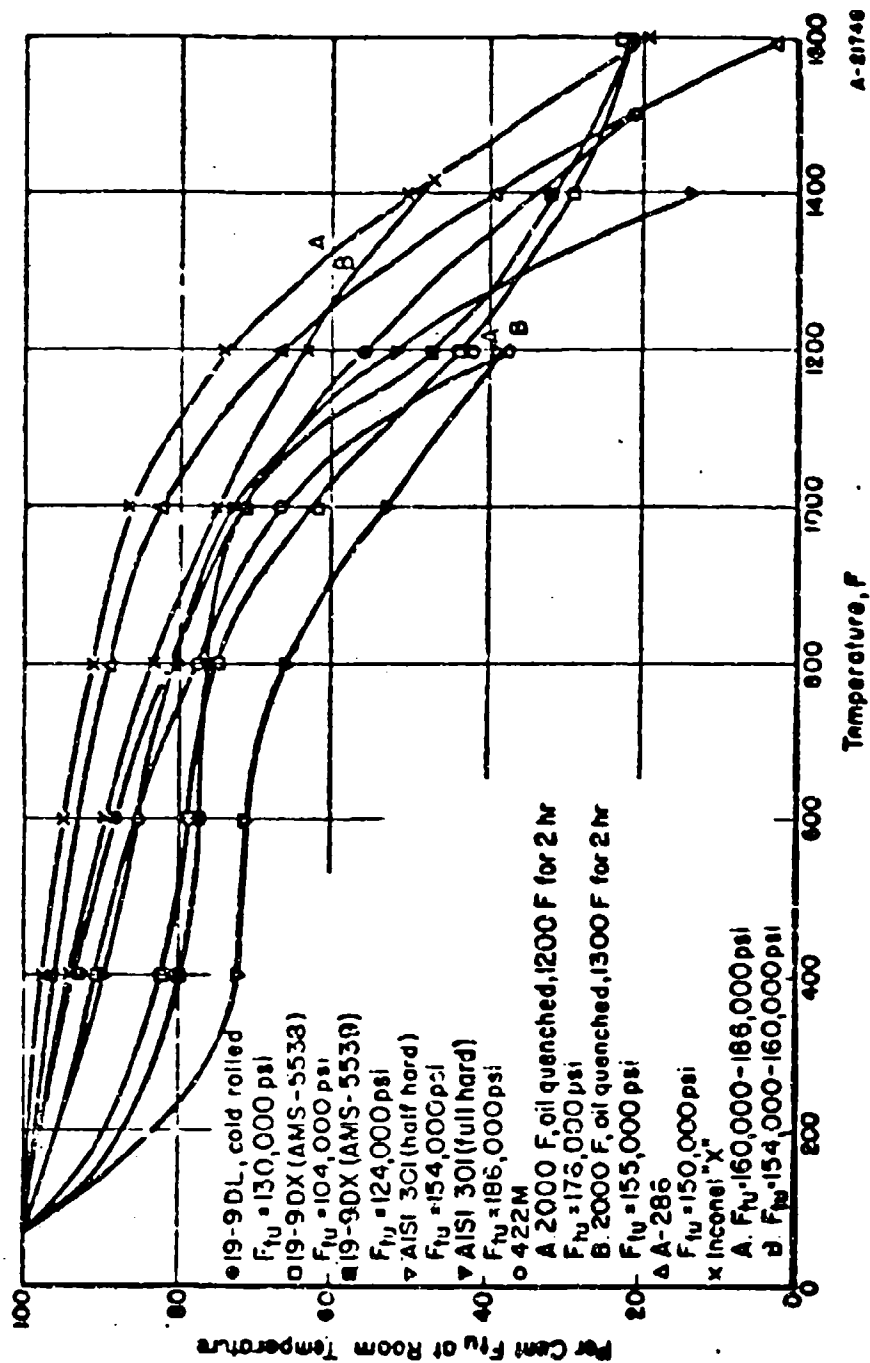


FIGURE 241. COMPARISON OF TENSILE STRENGTHS (F_{T_u}) OF STAINLESS STEELS AND SUPER ALLOYS AT ELEVATED TEMPERATURE

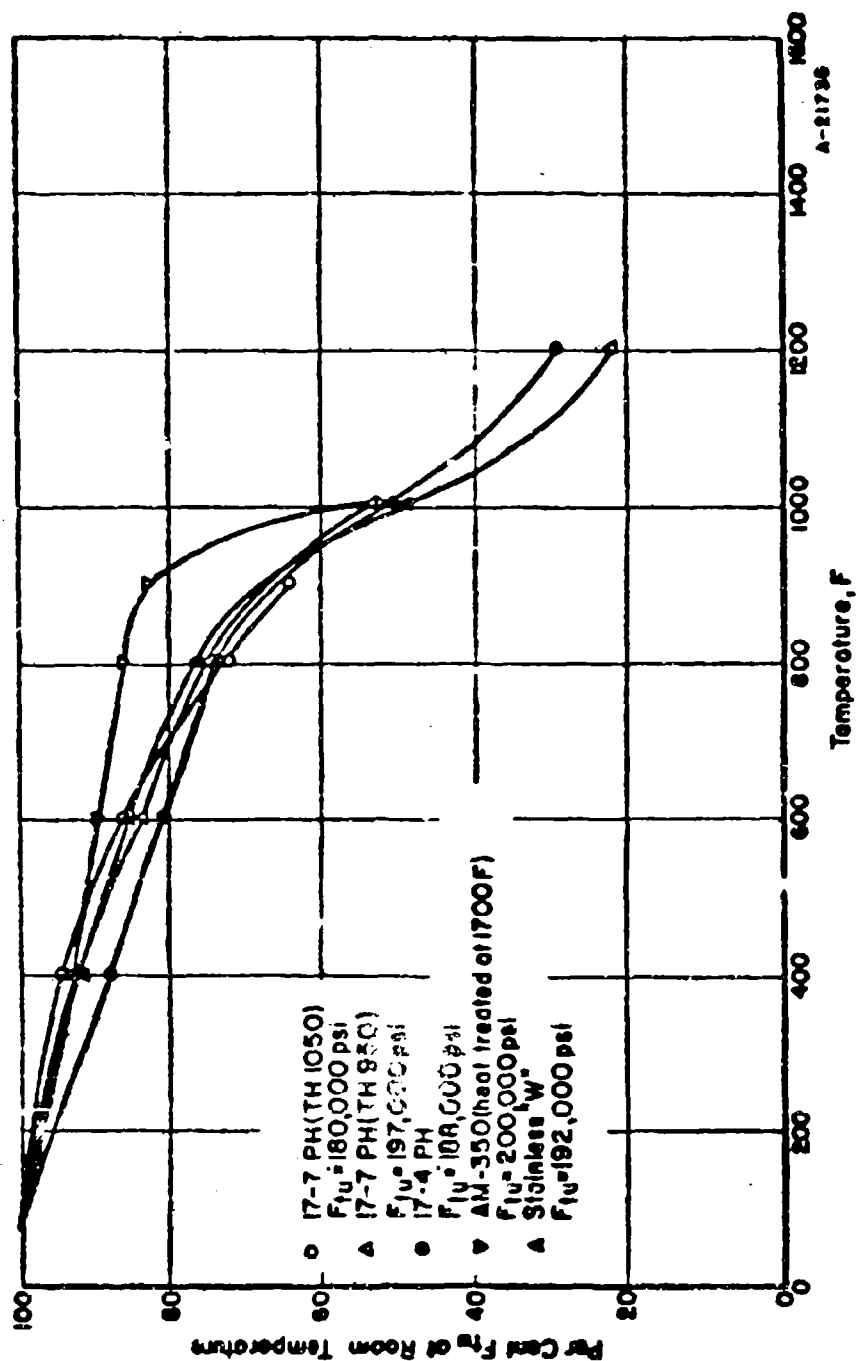


FIGURE 242. COMPARISON OF TENSILE STRENGTHS (F_{tu}) OF PRECIPITATION-HARDENABLE STAINLESS STEELS AT ELEVATED TEMPERATURE

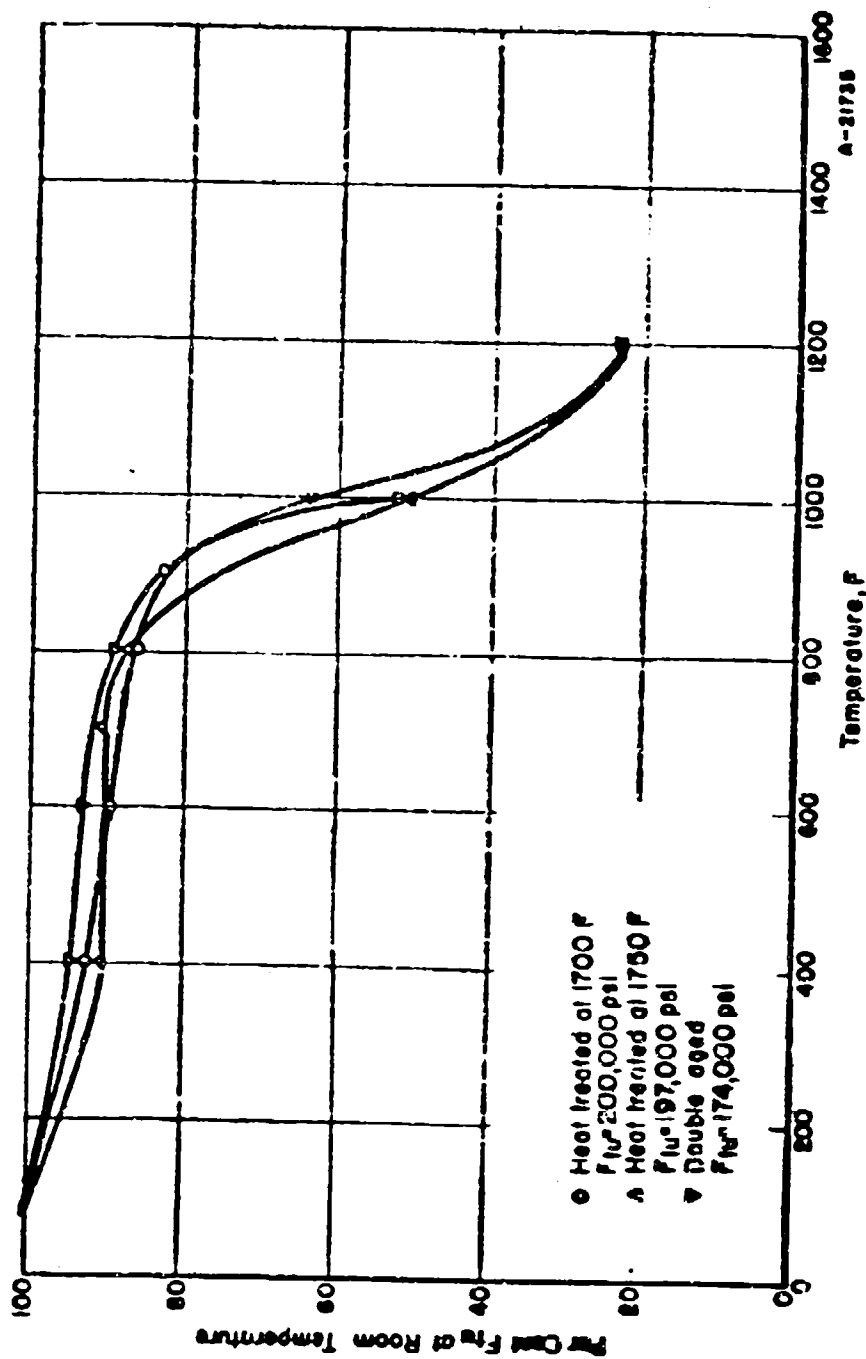


FIGURE 243. COMPARISON OF TENSILE STRENGTHS (F_{T}) OF AM-350 STAINLESS STEEL AT ELEVATED TEMPERATURE

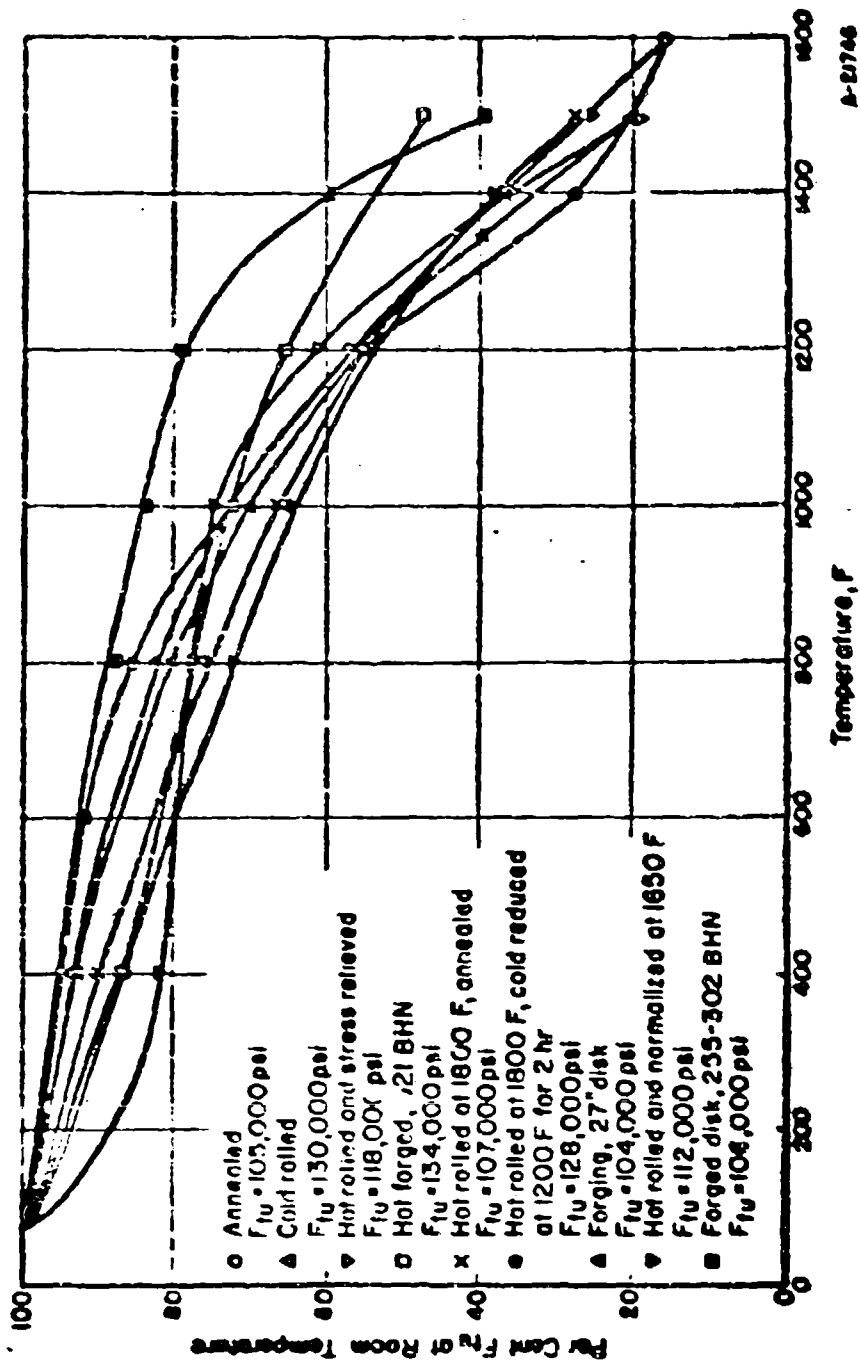


FIGURE 244. COMPARISON OF TENSILE STRENGTHS (F_{TU}) OF 19-9DL STAINLESS STEEL AT ELEVATED TEMPERATURE

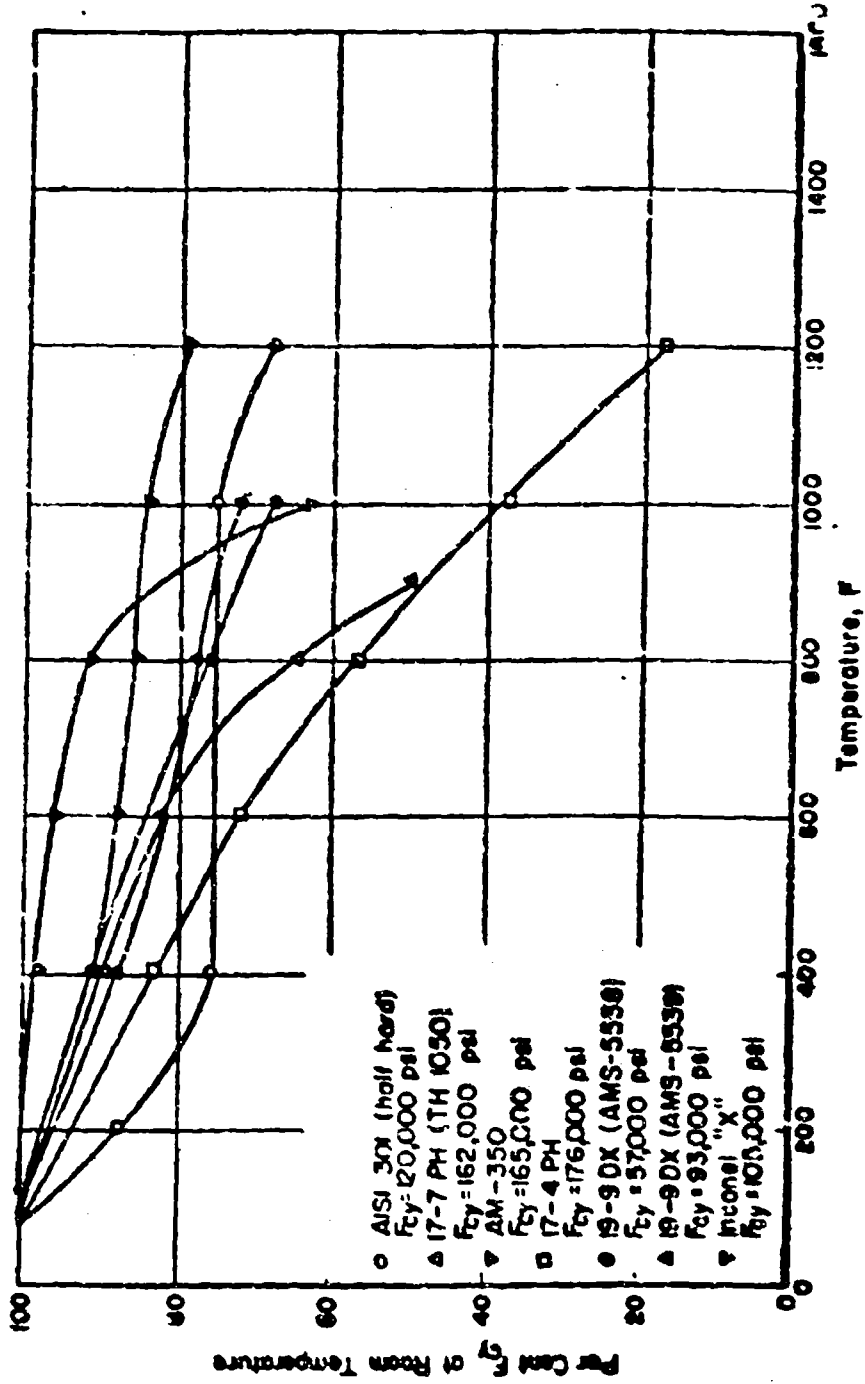


FIGURE 245. COMPARISON OF COMPRESSIVE YIELD STRENGTHS (F_{cy}) OF STAINLESS STEELS AND SUPER ALLOYS AT ELEVATED TEMPERATURE

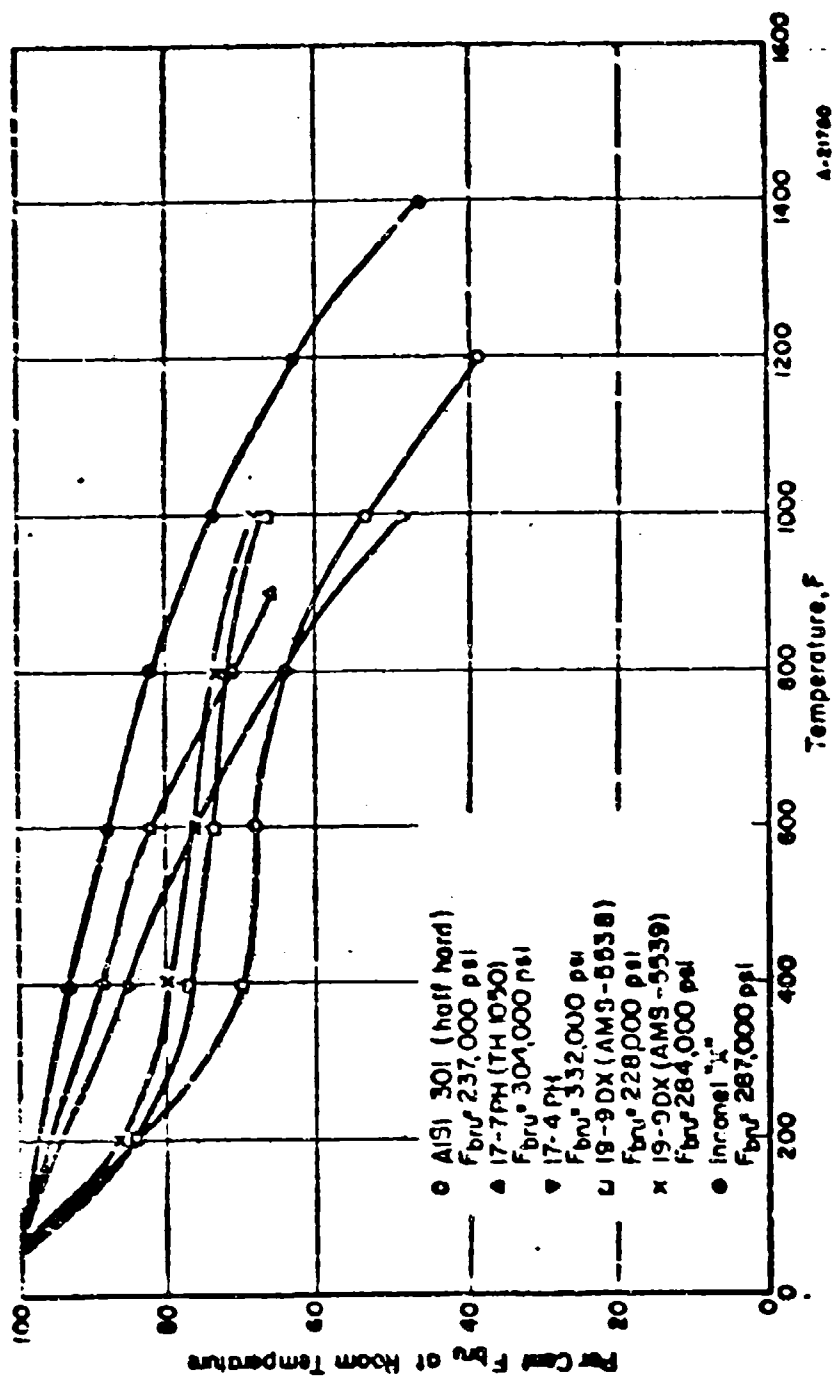


FIGURE 246. COMPARISON OF BEARING STRENGTHS (F_{b-u}) OF STAINLESS STEELS AT ELEVATED TEMPERATURE

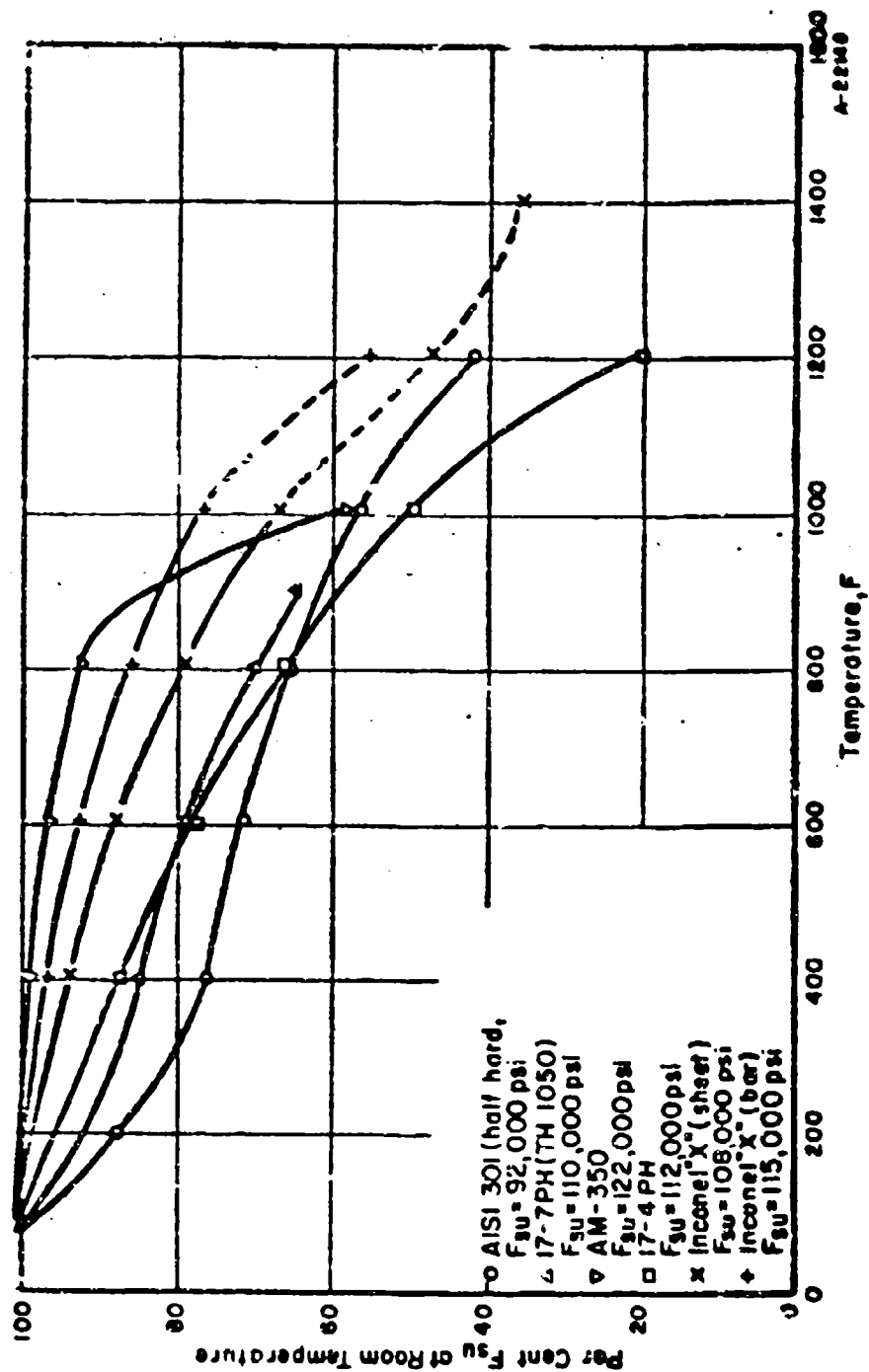


FIGURE 247. COMPARISON OF SHEAR STRENGTHS (F_{su}) OF STAINLESS STEELS AT ELEVATED TEMPERATURE

APPENDIX II

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